Implementation of a Comprehensive On-Line Closed-Loop Diagnostic System for Roll-to-Roll Amorphous Silicon Solar Cell Production

Introduction

- *-- ECD and United Solar*
- *-- ECD/United Roll-to-Roll Production Technology*
- *-- Impact of NREL PV MaT/Man Funding*

Summary of Phase I of the PV Man R&D 6 program

- ***Task I**: Implement Closed Loop Control of Film Thicknesses*
- ***Task II**: Component Cell PVCD development – for use in future continuous online optimization*
- ***Task III**: Plasma Diagnostics/Improved Deposition Technology*
- ***Task IV**: Yield Improvements: Substrate Cleaning – prove efficacy of plasma cleaning and get rid of washing machine*

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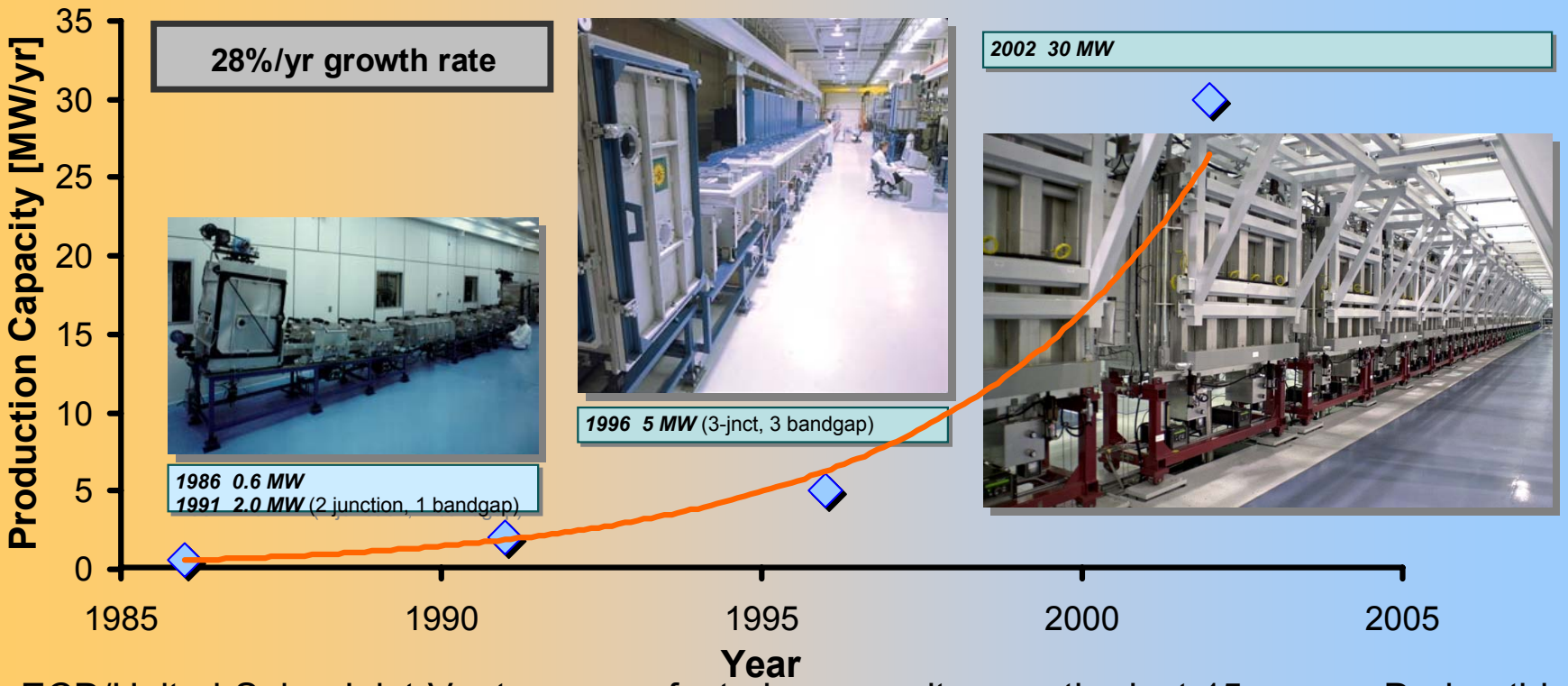
-ECD/United Solar-



ECD/United Solar Joint Venture manufacturing capacity over the last 15 years. During this time capacity has expanded at about 30%/year, with more rapid expansion in the last 5 years.

To see a World in a Grain of Sand
And a Heaven in a Wild Flower
Hold Infinity in the palm of your hand
And Eternity in an hour

William Blake, Augeries of Innocence

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-ECD/United Solar-

New 30 MW Manufacturing Facility in Auburn Hills MI

January 03 – Production Mode

March 03 – 5 MW Production Facility shunt down

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-ECD/United Solar Production Technology-

Roll-to-Roll a-Si production Technology

4 Roll-to-Roll Machines:

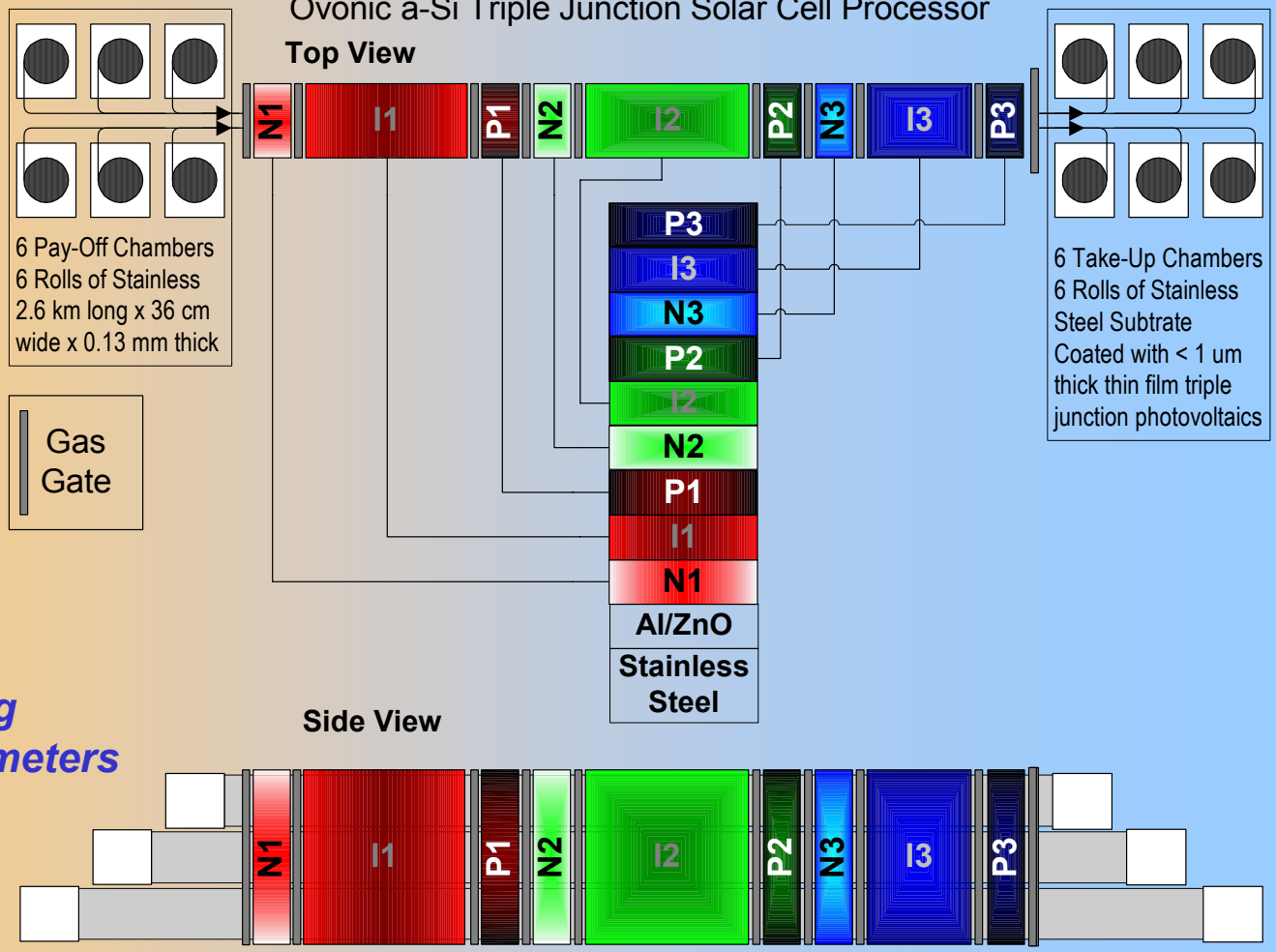
- -- Washing Machine (WM)
- -- Backreflector (BR)
- -- a-Si (30 MW)
- -- ITO Machine (ITO)

30 MW

- -- 6 x 2500 m rolls
- -- triple junction

PV MaT 5A Technologies:

- -- New NiChrome Heaters
- -- New Cathode Design
- -- "Pinch" Valves
- -- Reactive ZnO Sputtering
- -- The PVCD and Spectrometers



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-United Solar BIPV Products-

First metal roofing PV Installation [NAHB RC 21st Century Townhouse Project in Maryland]. DOE PV:BONUS Program.

Architecturally- and aesthetically-integrated *Uni-Solar* shingle (left) and metal-roofing BIPV installations made from lightweight, flexible, rugged a-Si thin film PV.

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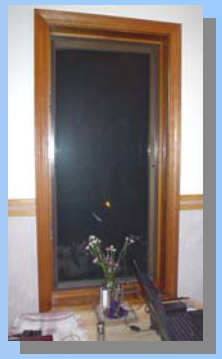
Where have we come from?

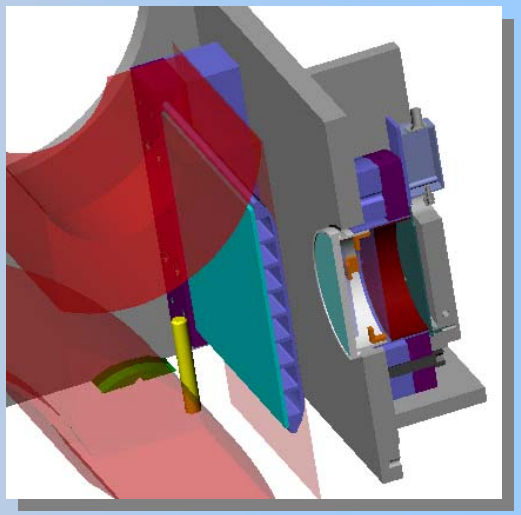
Pre-PVMaT 5 *– Windows in the Take-Up (TU) Chambers*



Post-PVMaT 5 *– 1 PVCD and 1 Spectrometer in 5 MW TU Chamber*
-- Limited QA; Some QC and Diagnostics

Development of New "Eyes"

Can "see":
-- Thickness
-- V_{OC}
-- J_{SC}/C, …



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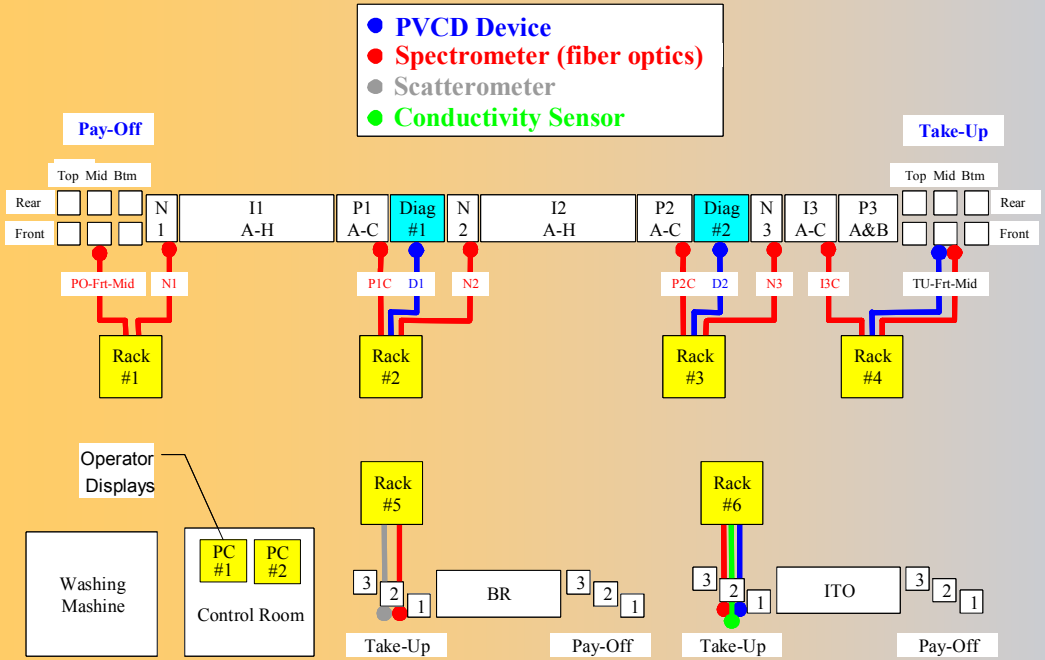
PV Man R&D 6: Where are we going?



Online Characterization
Online QA/QC
Developing:
- ***Closed-loop Thickness Control***
- ***Continuous Online Optimization***

≈ 10 Networked Computer DAQ Systems

10's of Diagnostic Systems

Roll-to-Roll Processor	Diagnostic Systems	Number	Measurement
Washing Machine	Optically Stimulated Electron Emission (OSEE)	2	Cleanliness
Backreflector	Scatterometer	1	Specular and diffuse reflection
	Reflection Spectrometers	1	ZnO film thickness
30 MW a-Si	Reflection Spectrometers	8	Thickness of BR and each n-, i-, and p-layer
	PVCD	4	Component and device electrical properties
ITO	Film conductivity	1	ITO conductivity
	Reflection Spectrometers	5	ITO film thickness
	PVCD	1	Device electrical properties; degree of shunts prior to passivation.

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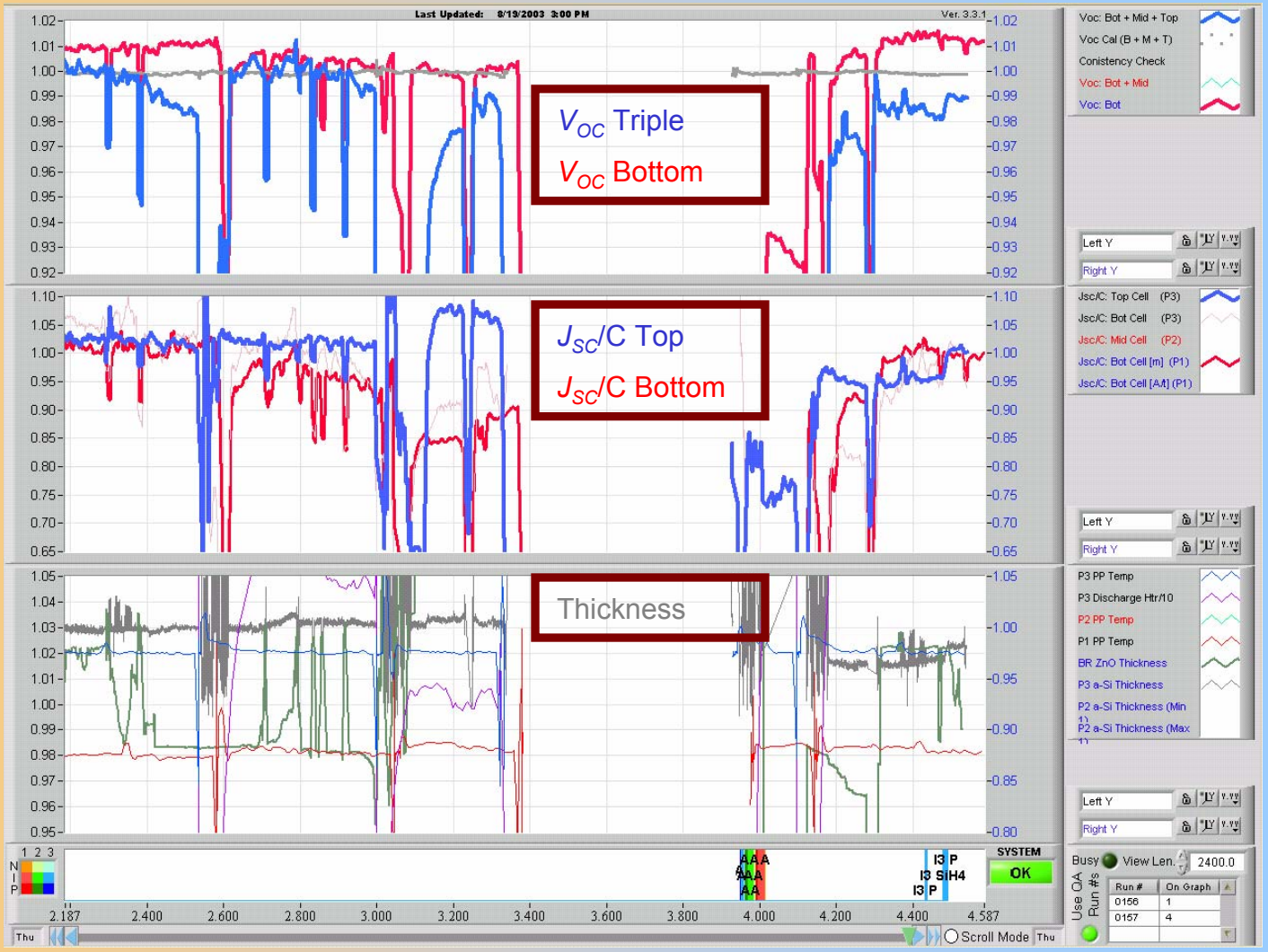
Success – What this Program is Yielding



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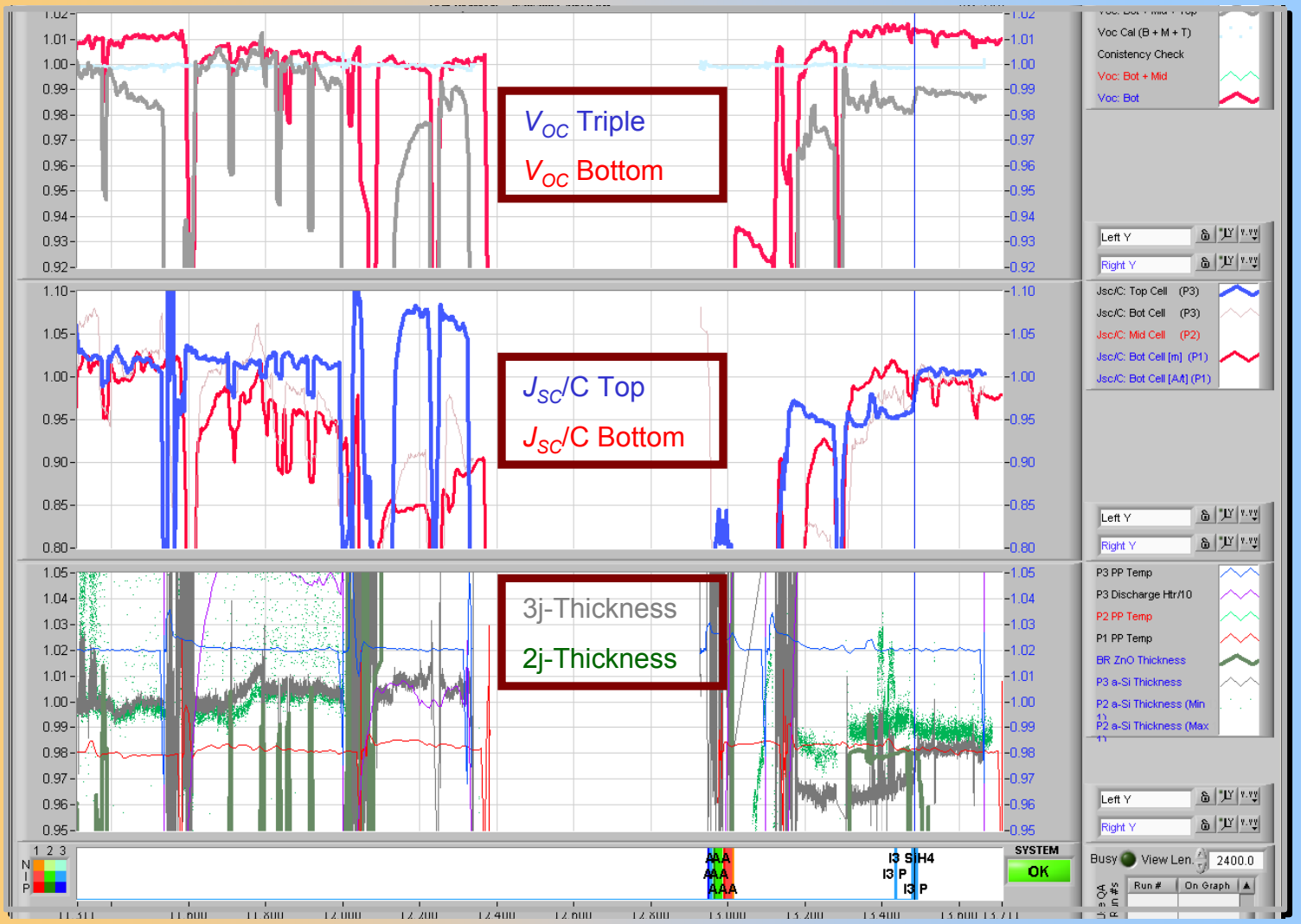

Thur 28 Aug 03
NREL – Annual Review

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A Whole New Regime

Questions –

The 30 MW has hundreds, if not thousands, of significant knobs. With 1-week turn-around of an experiment, how long would it take to completely optimize this machine?

How long to then optimize the 30 MW with the BR and ITO?

Think about this:

The R&D reactors can produce 1 – 3 samples/day, with poor statistics

With a complete online diagnostics systems we can perform hundreds of experiments/day 24/7 – with good statistics and no question about applicability to production.

How does one "automate" the experiment and experiment analysis process?

Can you symbiotically perform research on a production machine?

Production: Never change anything
Goal: make the exact same thing everyday

R&D: ***Constant*** *experimentation; change everything*
Goal: all material above average

YES -- while we admit that the primary purpose of the machines may be production, we are demonstrating that simultaneous R&D can benefit production.

We have developed a very good working relationship with the production personnel

-- this is the most significant breakthrough in production technology in the last 10 years.

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ECD and United Solar PV Manufacturing R&D Program

Comprehensive On-Line Closed-Loop Diagnostic Systems

Program Overview

Work Areas:

1. **Closed Loop Thickness Control in the ITO, BR, *and a-Si Machines***
   Thickness measurement of all 9 layers in the triple junction a-Si device.
   Phase I: Instrument BR, ITO, and a-Si TU; Second Generation a-Si Spectrometer
   Design ITO and BR Closed Loop Thickness Control System

2. **Component Cell PVCD Development**
   *V_{OC}, J_{SC}/C and other measurements of **each cell** in the triple junction device*
   Implement Program of Continuous Online Optimization
   Phase I: Design, Fabricate, Install, Retrofit 1st Component Cell PVCD

3. **Plasma Diagnostics; Improving Deposition Hardware**
   Phase I: Install Diagnostics; Analyze Plasmas
   Study Particle Production in a-Si Machine

4. **Yield Improvements – Substrate Cleaning**
   Implement Plasma Cleaning – Eliminate 1 of 4 Roll-to-Roll Production Machines
   Phase I: Online Cleanliness Diagnostic in WM
   Correlate cleaning parameters with yield
   Test plasma cleaning; compare with wet chemical cleaning
   Determine and address most significant sources of yield reduction

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Task I: Closed Loop Thickness Control I

TASK 1: Develop Closed-Loop Control of Film Thickness

-- **Jeff Karn (ECD)**, Rujiang Liu and Jon Call (United Solar), Dave Dodge (Focus Software)

Milestones

Complete	M-1.0.1	Complete testing of 1st generation a-Si reflection spectrometer in production equipment.
Complete	M-1.1.1	Complete conceptual design of 1st generation ITO and ZnO closed-loop thickness-control systems.
Complete	M-1.2.1	Complete installation of 2nd generation a-Si reflection spectrometer in production equipment.
Complete	M-1.3.1	Complete fabrication of 1st generation closed-loop thickness-control systems for ITO and ZnO.
Complete	M-1.4.1	Complete the Phase I portion of the effort under Task 1.

Deliverables

Complete	D-1.0.1	Report summarizing the testing of the 1st generation a-Si reflection spectrometer in the production equipment.
Complete	D-1.2.1	Report summarizing closed-loop thickness-control systems fabricated for the ITO and ZnO film thickness
Complete	D-1.3.1	ECD/United Solar confidential datalog display from a complete production roll of material demonstrating a-Si spectrometer thickness measurements

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Comprehensive On-Line Closed-Loop Diagnostic Systems

Task I: Closed Loop Thickness Control I

- Overview
- First Generation a-Si Spectrometer
  - Hardware
  - Reflection Spectra
  - Software
    - Online DAQ
    - Online Operator Inteface
    - Offline Analysis Utilities
  - Stop and Burn Technology (Unplanned Benefit)
    - Trouble-shooting
    - Integrals – motivation for 2nd Generation a-Si Spectrometer
- Second Generation a-Si Spectrometer
  - Design (actually, this is second design – Needed the "A" team)
  - First Operation
- Closed Loop Thickness Control System (BR)
  - Spectra
  - "Manual" Looping; Motivation (stabilize process by stabilizing input)
  - System Design – looks straightforward … (don't quote me on that)
- ITO –
  - More Difficult than Initially Thought
    - Color
    - *Need to stabilize a-Si input!*

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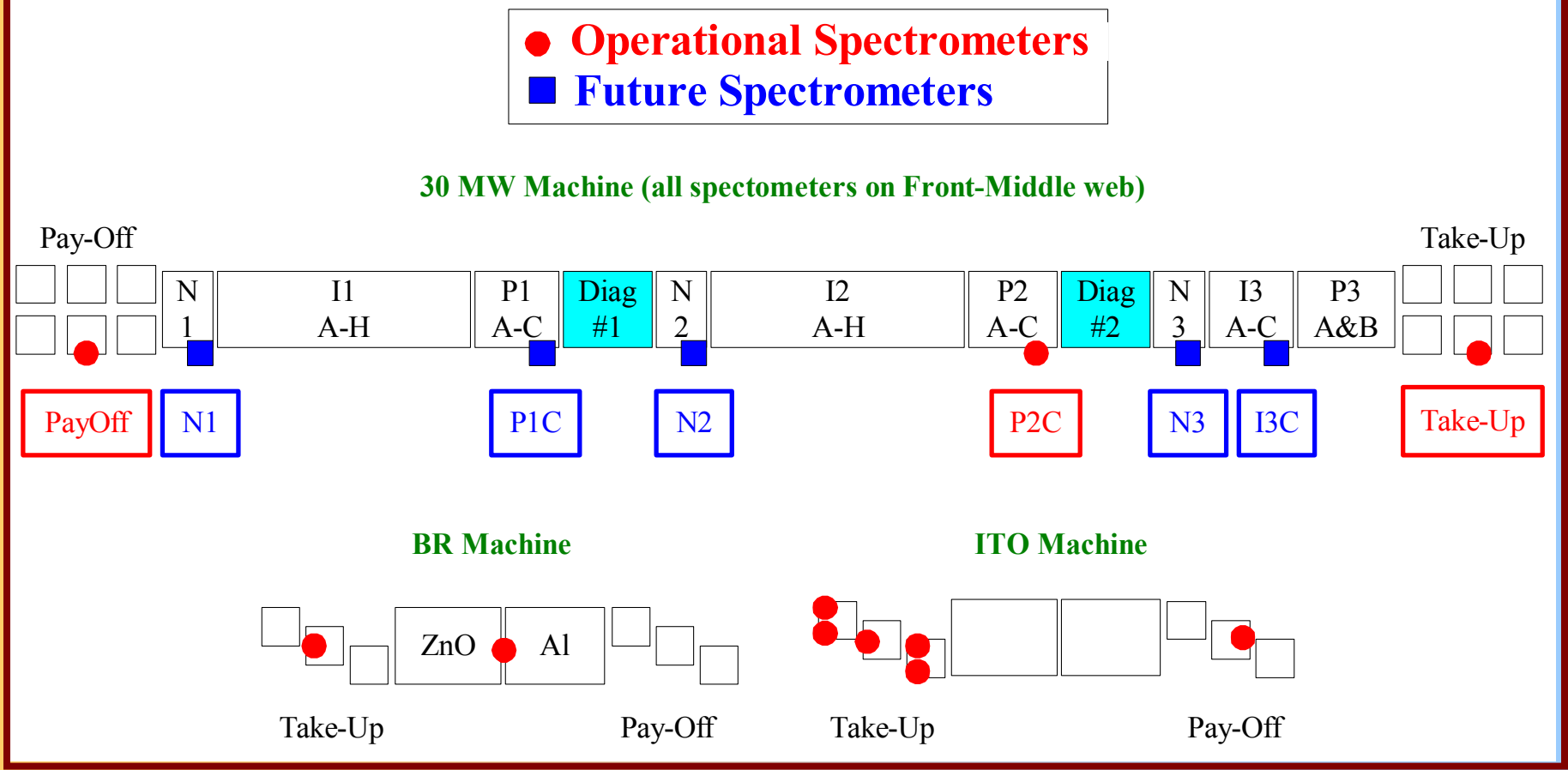
Overview



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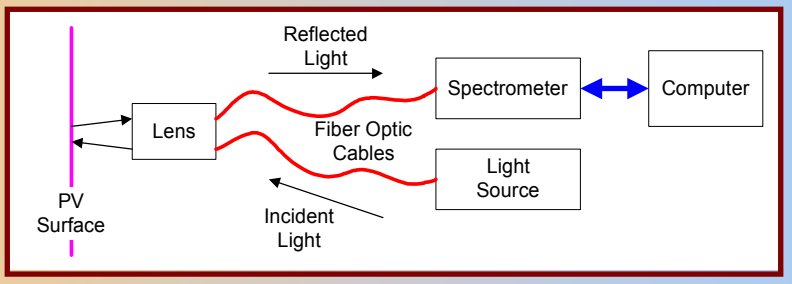
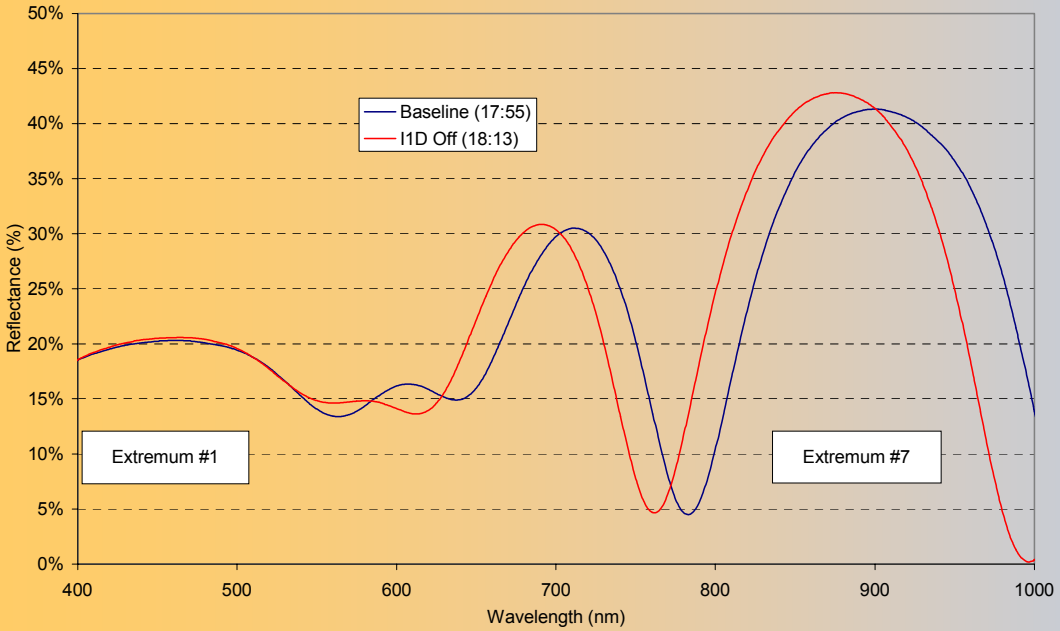
Comprehensive On-Line Closed-Loop Diagnostic Systems

Task I: Closed Loop Thickness Control I

Overview

Hardware and Typical Spectra





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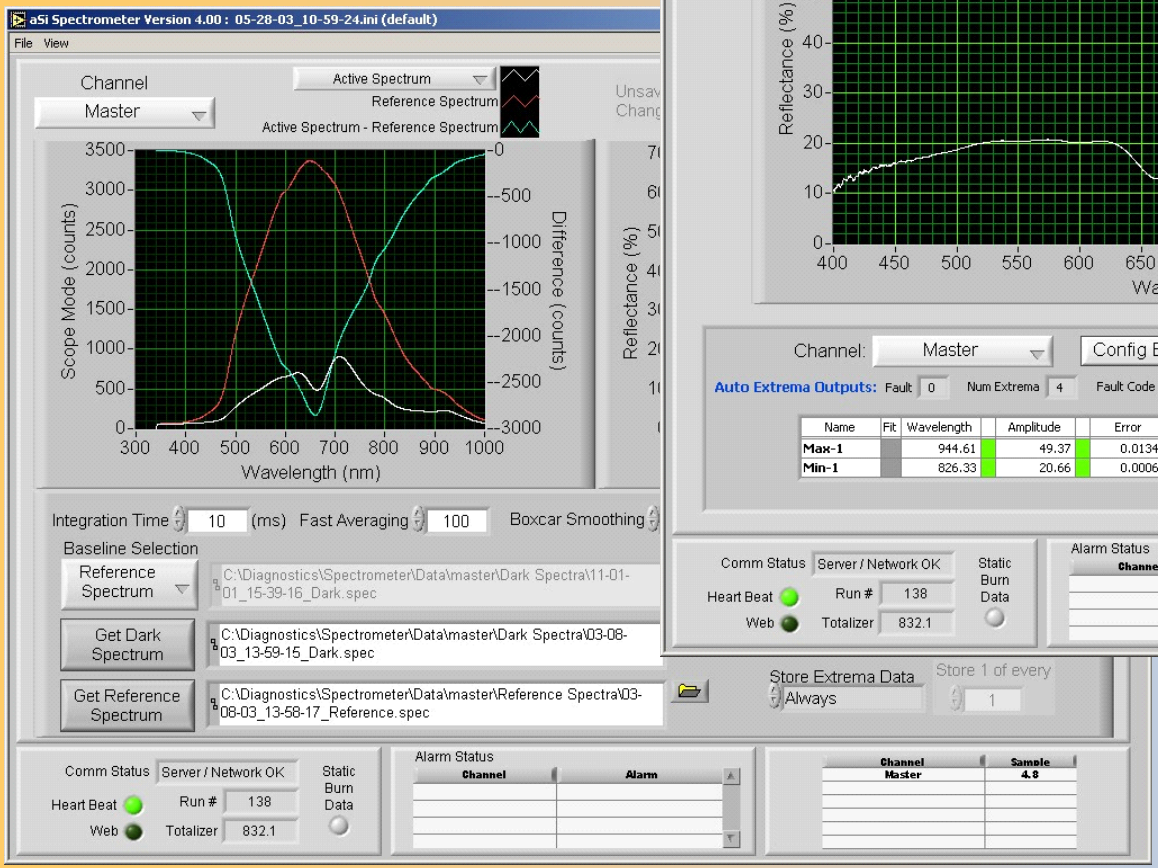
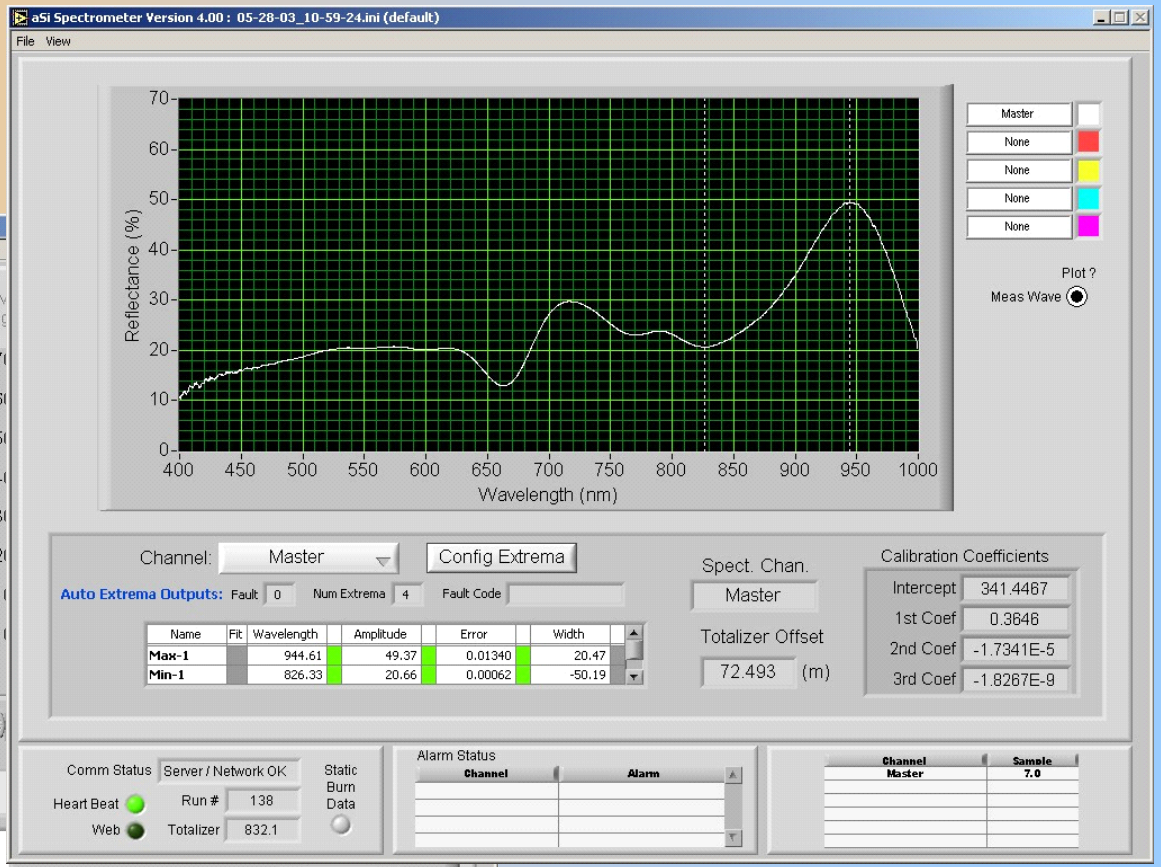
Task I: Closed Loop Thickness Control I

Software –

- Online DAQ
- Online Operator
- Offline Analysis Utilities





Expert and Details "Panels"

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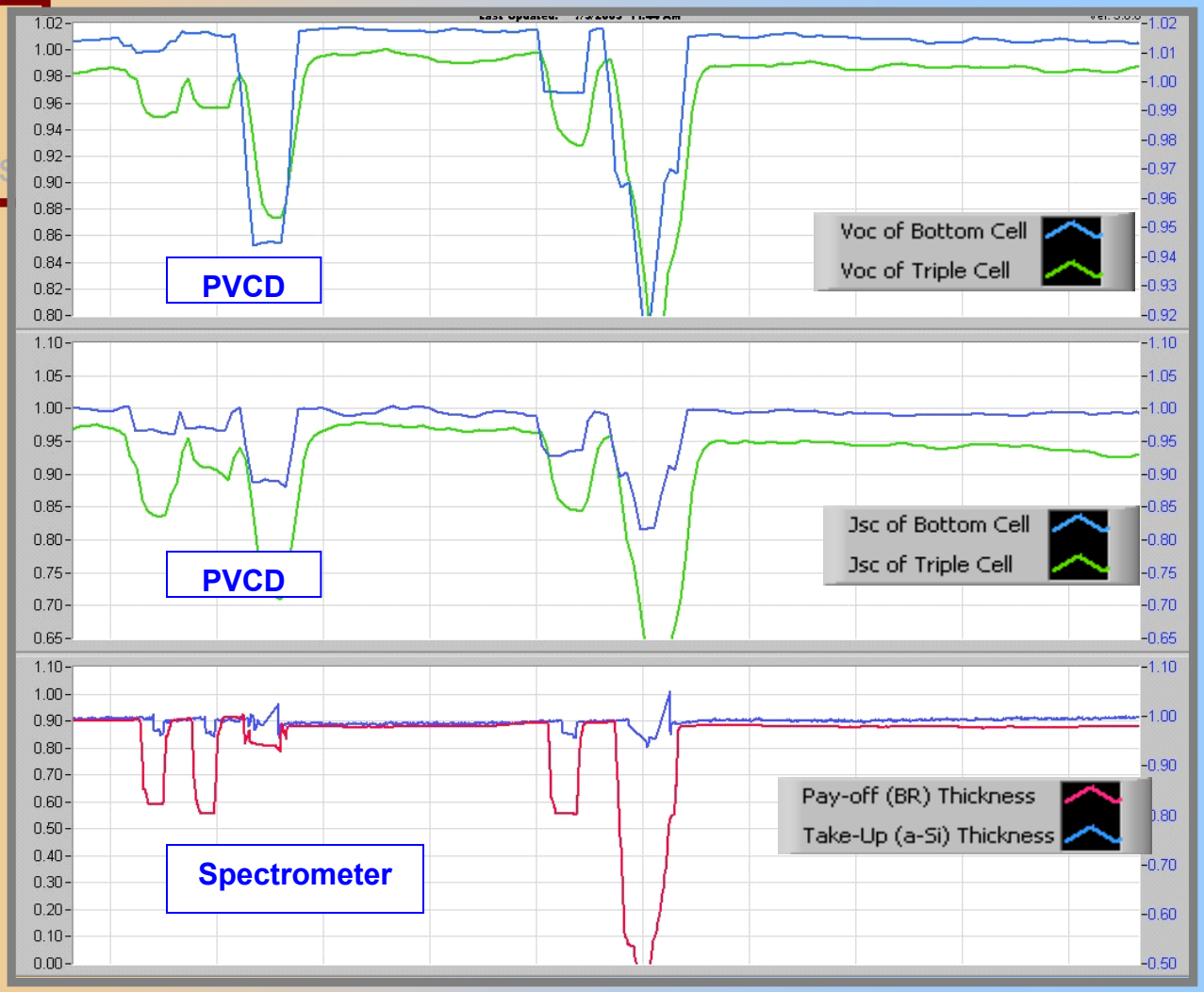
Task I: Closed Loop Thickness Control I

Software –

- Online DAQ
- Online Operator
- Offline Analysis Utilities



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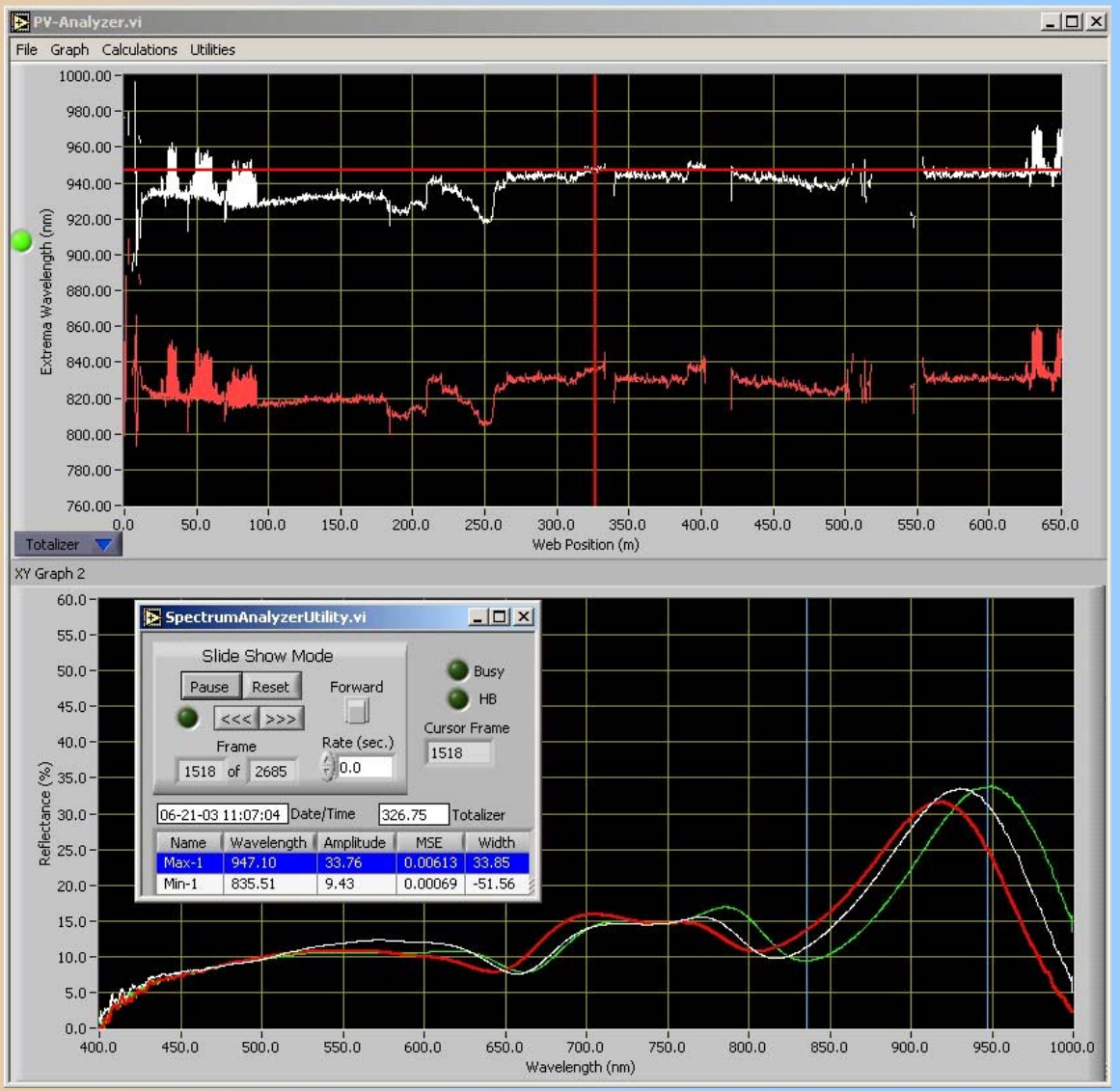
Task I: Closed Loop Thickness Control I

Software –

- Online DAQ
- Online Operator
- Offline Analysis Utilities

Raw Data (Spectra) are saved and archived so that old "Runs" can be played back to optimize fitting algorithms



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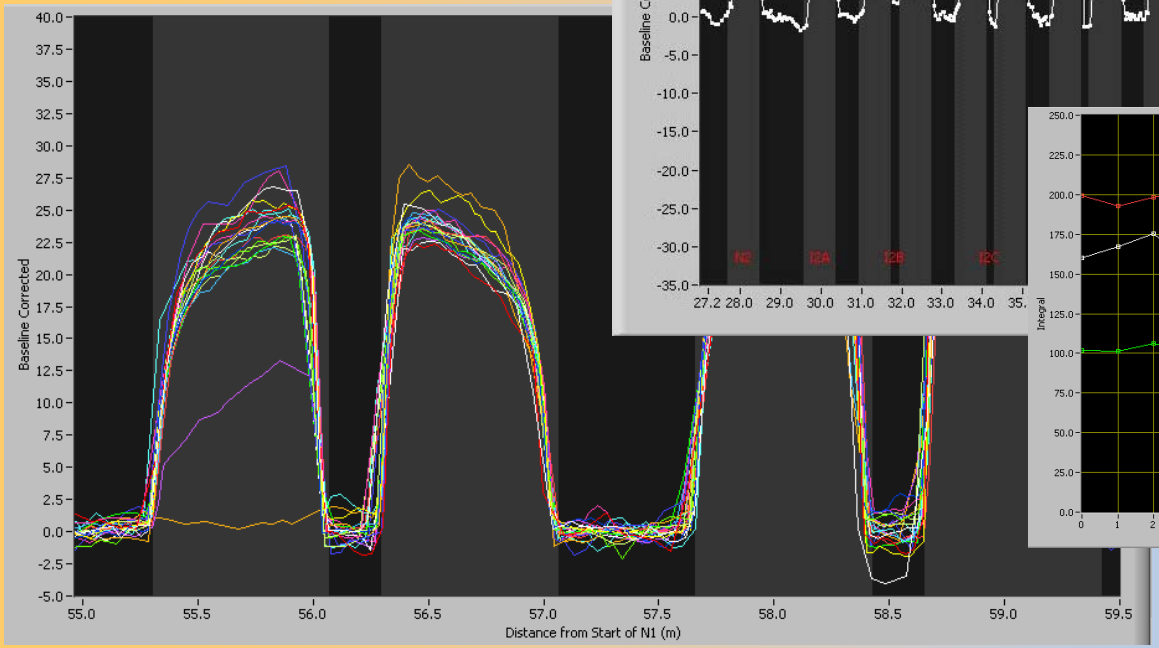
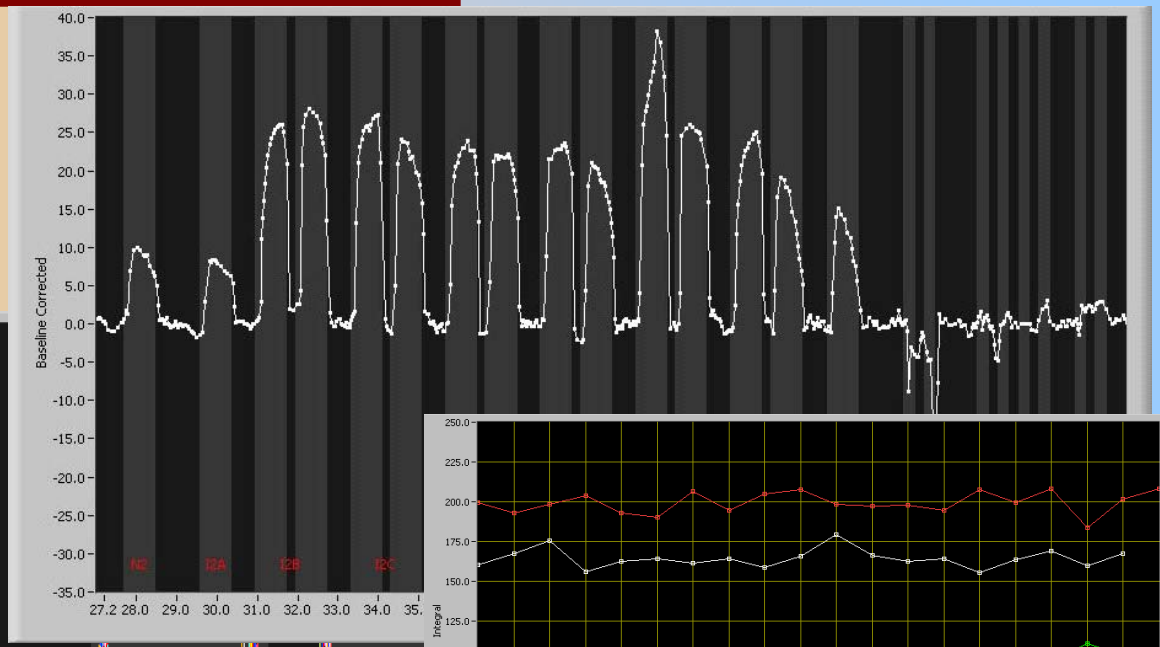
Task I: Closed Loop Thickness Control I

"1-min On-the-Fly Static Burn" Technology – Bonus!





Second Generation a-Si Spectrometer Motivation

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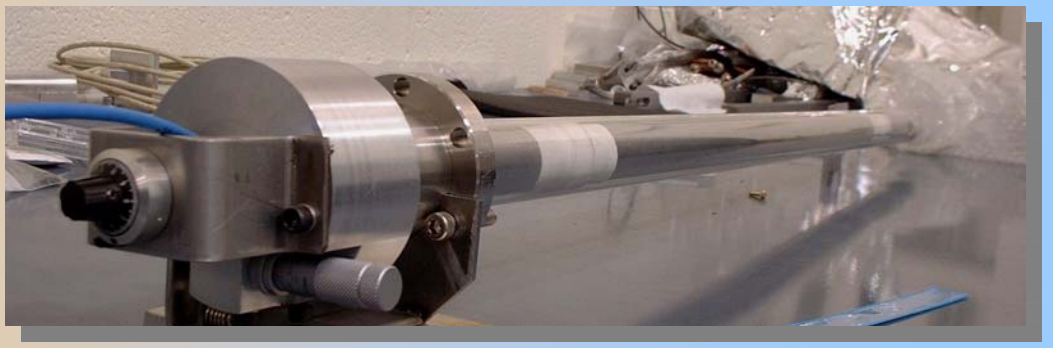
Second Generation a-Si Spectrometer

Design (really second design – Needed the "A" Team)

- 300 °C Temperatures
- Thermal Cycling
- UHV Compatible
- Avoid a-Si deposition on spectrometer optics
- Moving web must be free from vibration or angular changes
- Located inside a long narrow region between webs
- Hidden from visual inspection, hands-on adjustment



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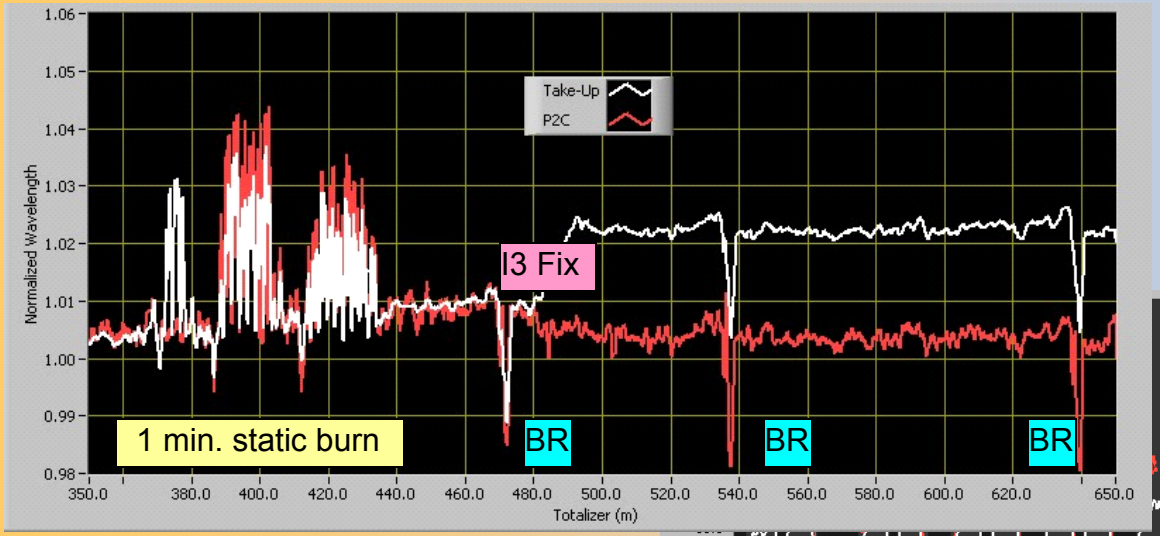
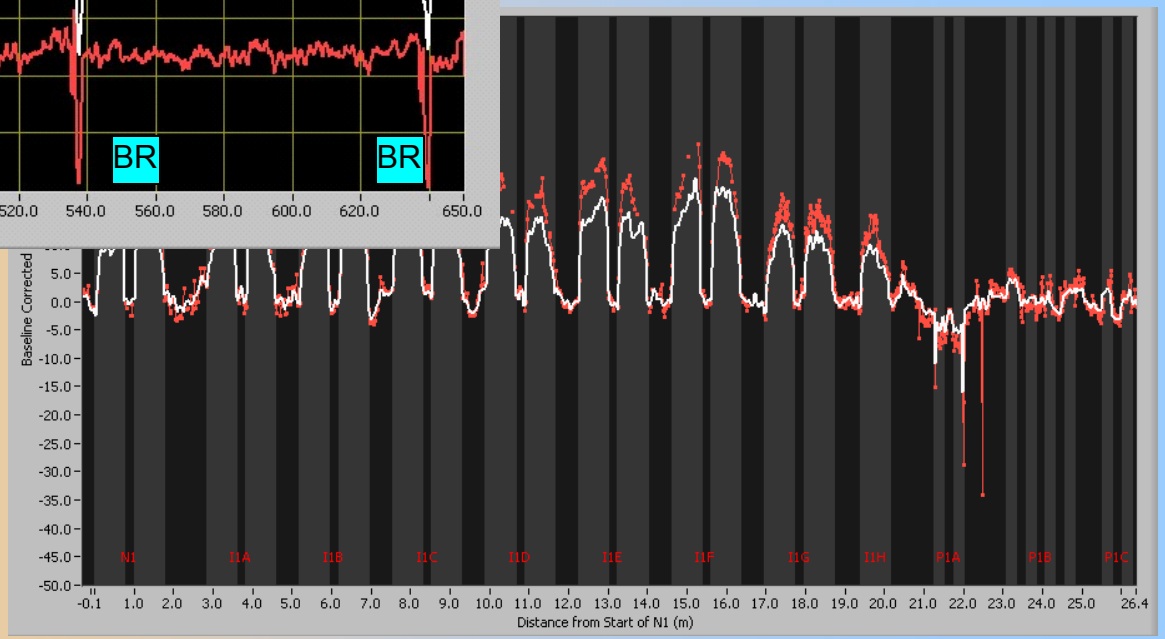
Second Generation a-Si Spectrometer
First Operation





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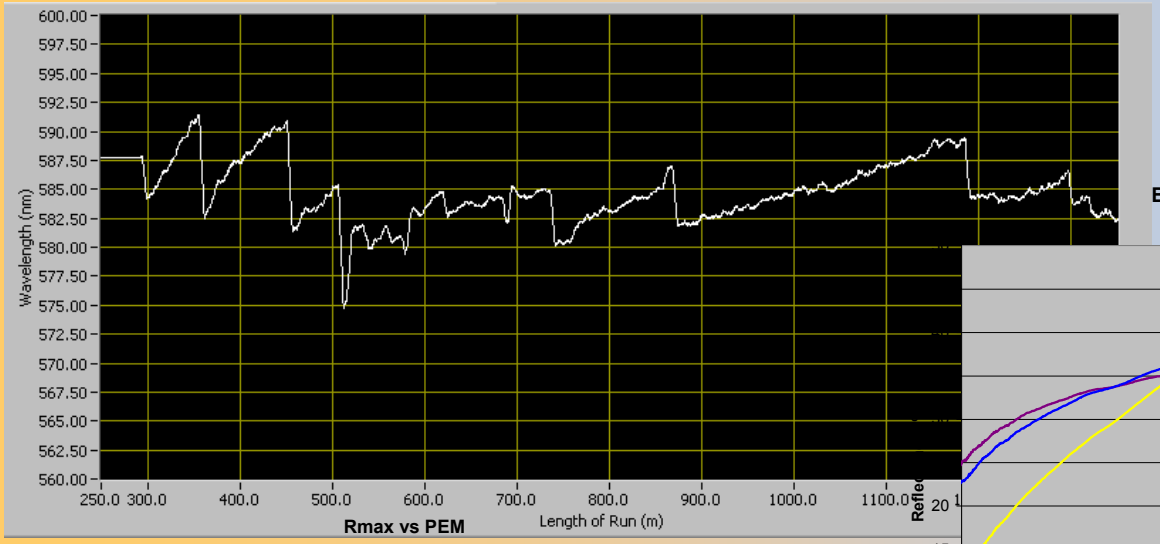
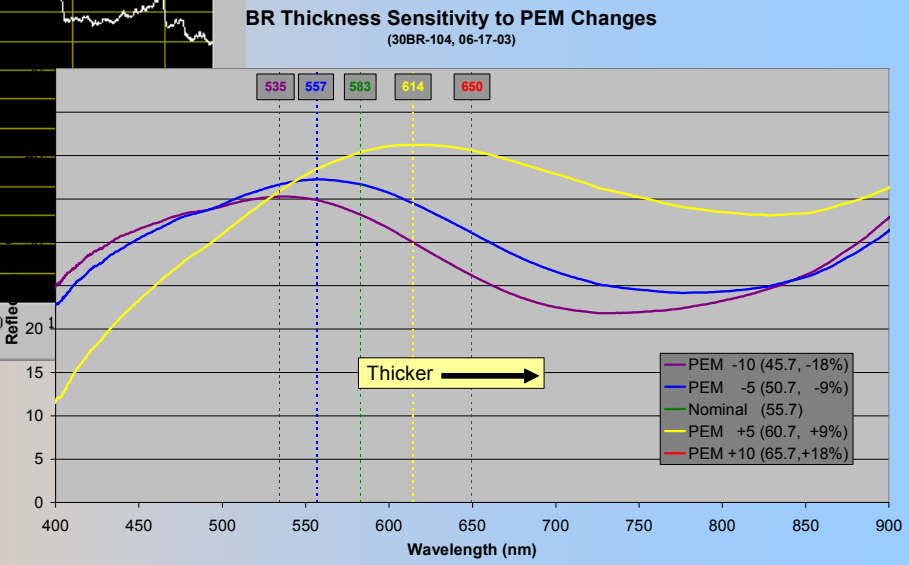
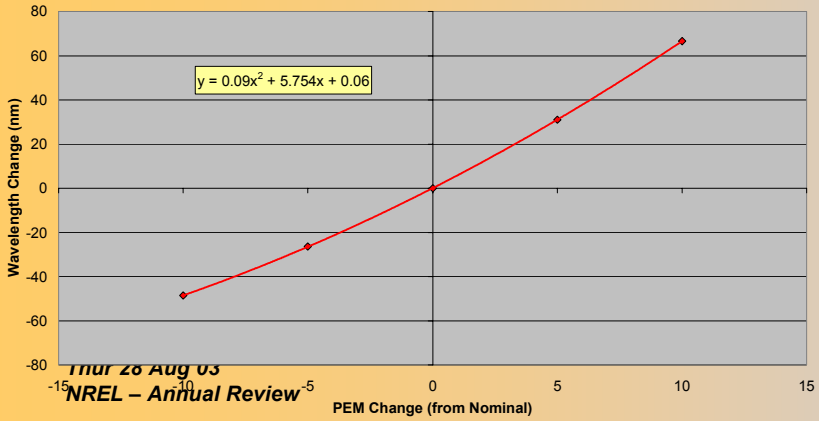
Task I: Closed Loop Thickness Control I

Closed Loop Thickness Control System (BR) (ITO is a can of worms!)
Presently humans close the loop –







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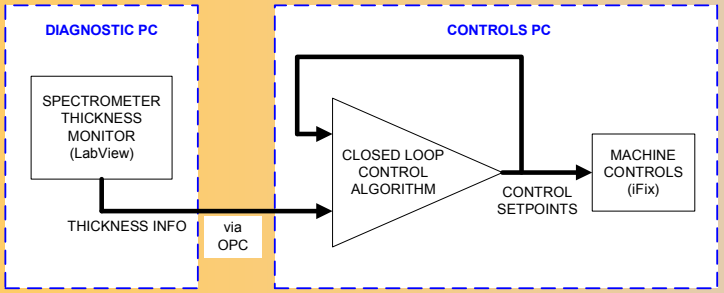
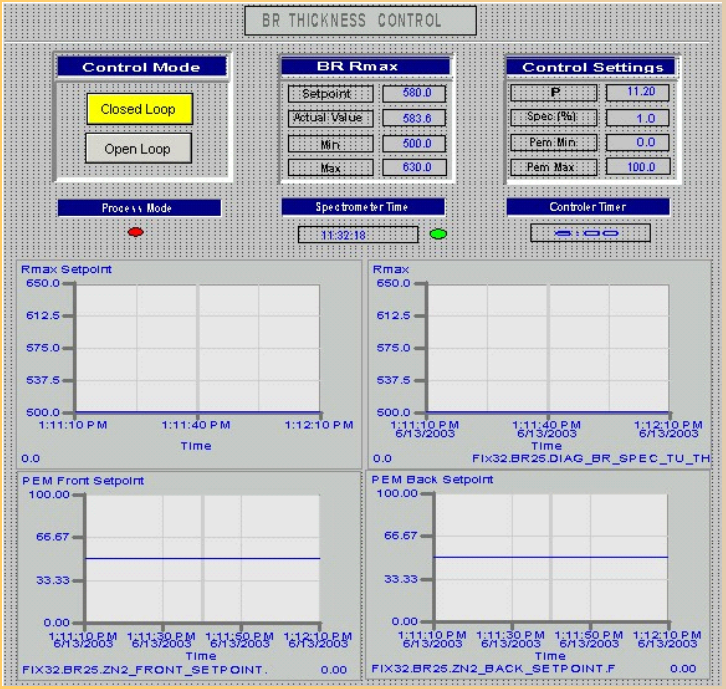
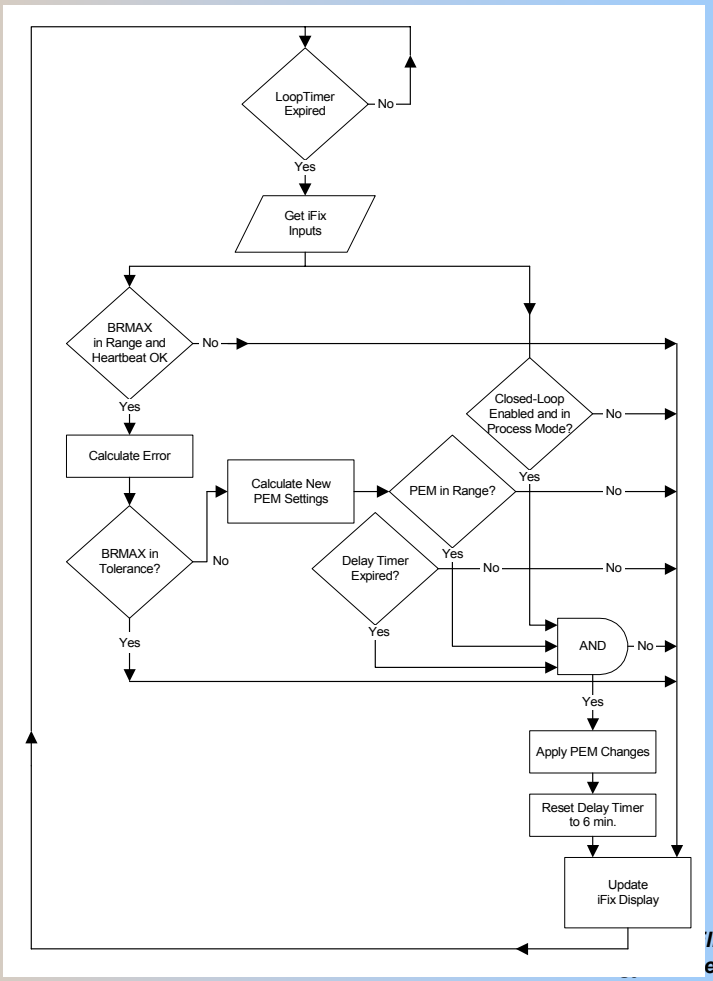
Task I: Closed Loop Thickness Control I

Closed Loop Thickness Control System (BR) (ITO is a can of worms!)
System Design – "Conceptually Simple" – the exceptions are what will get us







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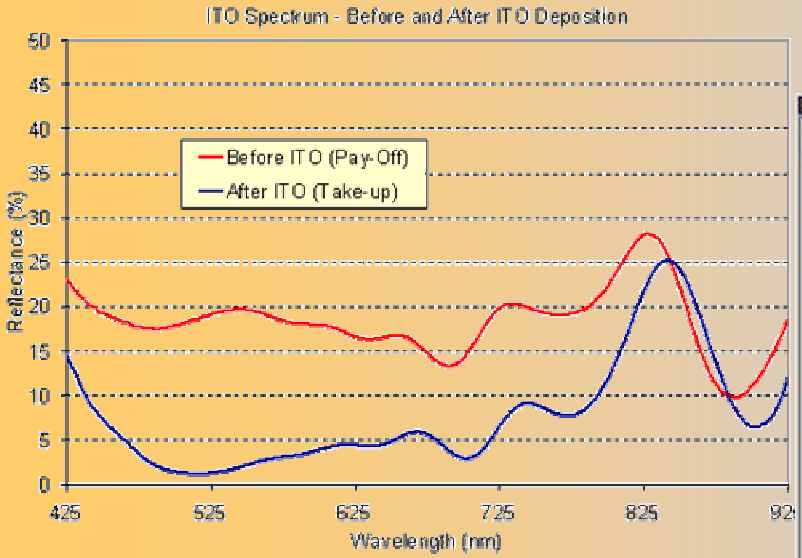
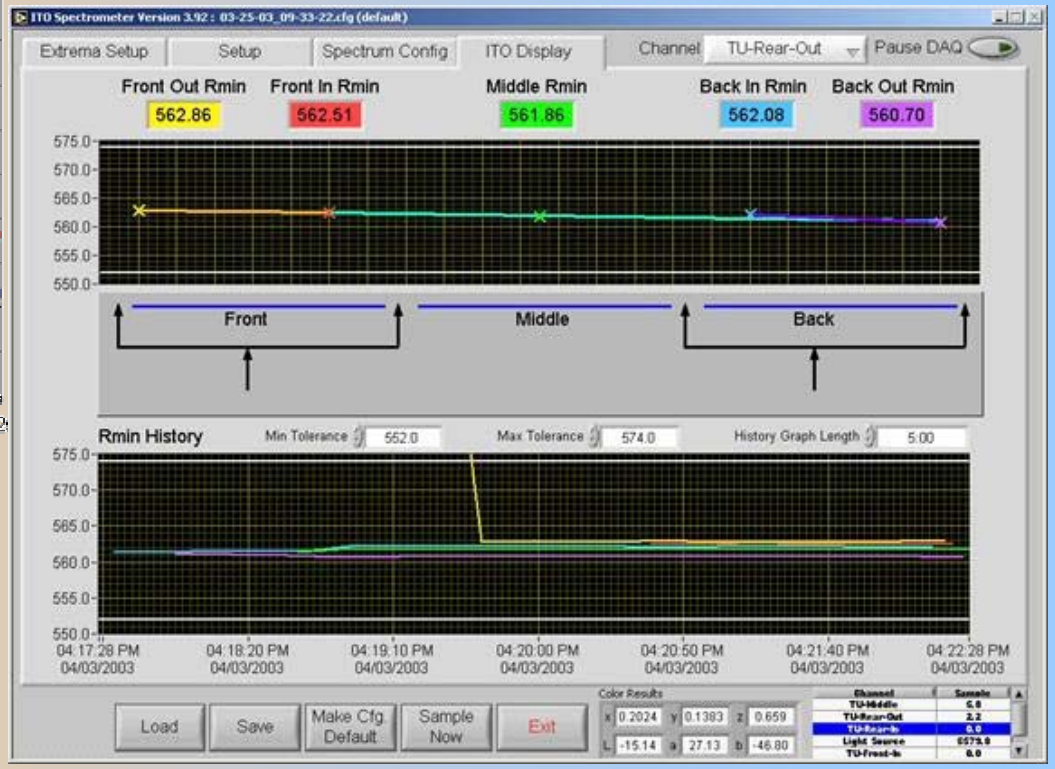
Task I: Closed Loop Thickness Control I

Closed Loop Thickness Control System
ITO not conceptually simple --





Color more important than thickness

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Task I: Closed Loop Thickness Control I

Closed Loop Thickness Control System
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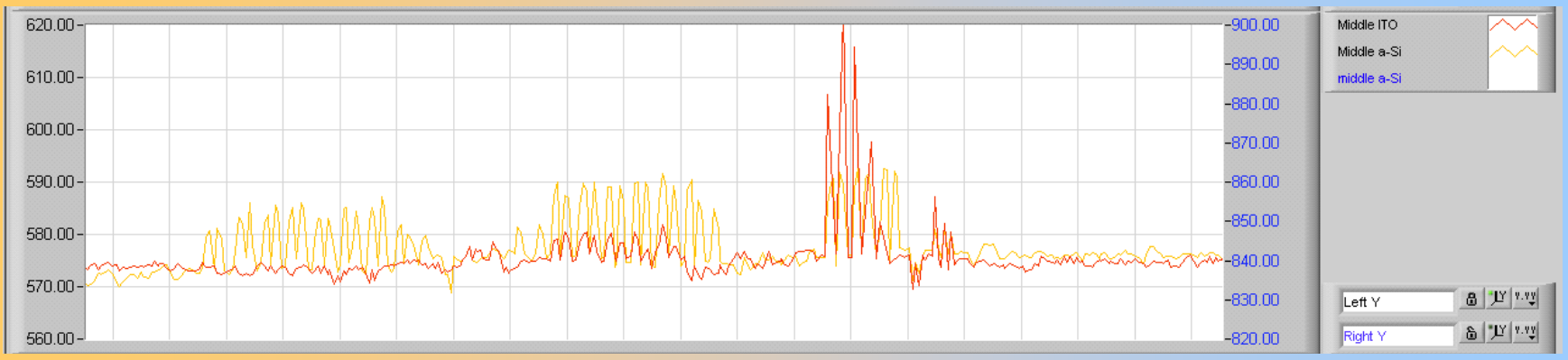

Top Layer a-Si thickness affects reflection spectrum, and consequently color
Best way to control output is to control input
While we had initially thought controlling a-Si thicknesses was beyond the scope of this program, we are now more highly motivated
Will try, initially manually, closing the loop on a-Si top cell thickness before closing the loop on ITO thickness (color).

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Task 2: Component Cell PVCD

TASK 2: PV Capacitive Diagnostic Design and Fabrication for Bottom and Middle Cells

– **Tim Ellison**, Rob Kopf and Wayne Messing (ECD); Dave Dodge (Focus Software)

Milestones

Complete	m-1.0.2	Complete initial bench testing of component cell PVCD.
Complete	m-1.0.3	Complete bench testing of component high intensity LED light source and light source power supply.
Complete	m-1.1.2	Complete preliminary testing of component cell PVCD in production machine.
Complete	m-1.3.2	Complete installation of retrofitted component cell PV Capacitive Diagnostic in production equipment.
Complete	m-1.4.2	Complete the Phase I portion of the effort under Task 2.

Deliverables

Complete	D-1.0.1	Report summarizing bench testing of high intensity LED light source and light source power supply
Complete	D-1.1.1	Report summarizing design and installation of component cell PV Capacitive Diagnostic in production equipment.

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Component Cell PVCD:
Design, Fabrication, Testing, Installation, Optimization

- Background – PV MaT 5A Development
- Motivation
- Design
  - Challenges
  - Shutter System
  - Design Summary
  - Light Source
- Installation (x3)
- Optimization
  - First Operation/Noise
  - Plasma Noise Killer
- Summary

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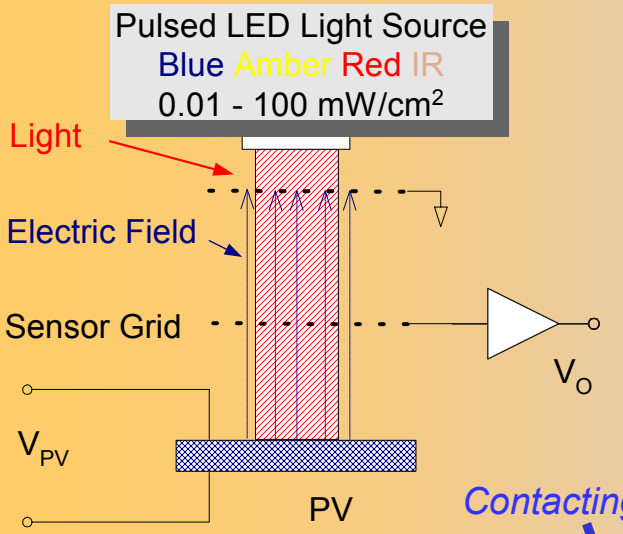
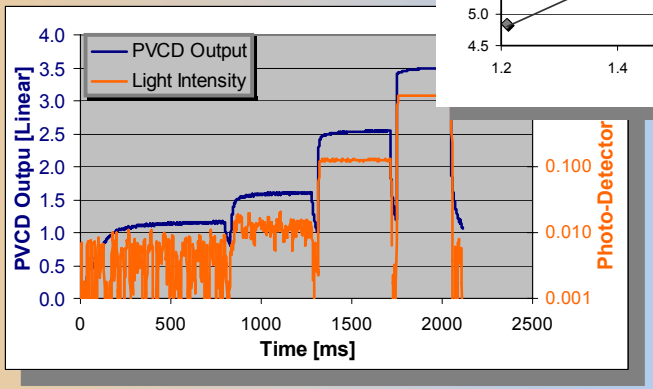
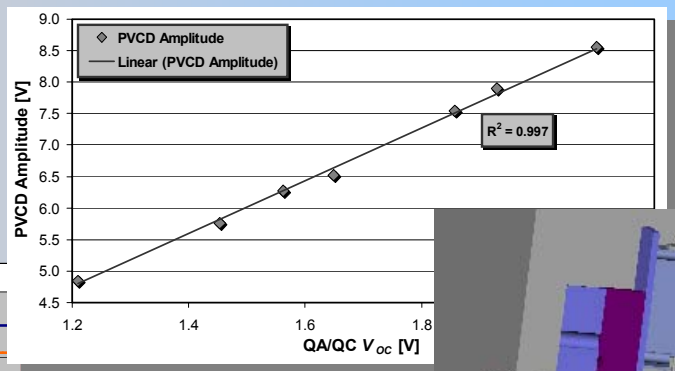
Comprehensive On-Line Closed-Loop Diagnostic Systems

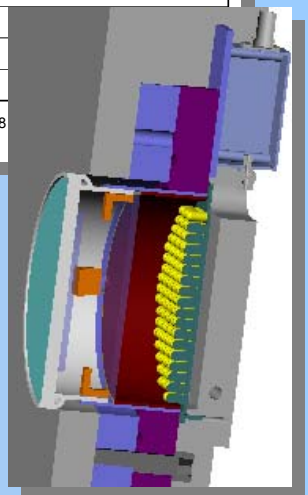
Task 2: Component Cell PVCD

Component Cell PVCD: Background – PV MaT 5A

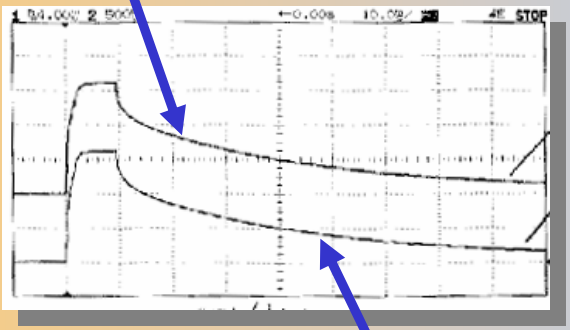








Contacting Measurement



Non-Contacting PVCD Measurement

> 10 Independent Parameters in PVCD Waveform – 2 trivial and well established:

Amplitude: V_{OC}

Initial Derivative: J_{SC}/C

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Task 2: Component Cell PVCD

Motivation –

Unambiguous V_{OC}, J_{SC}/C , and ? measurements for each component cell

- Pinpoint Problems – especially when combined with other diagnostics data (e.g. spectrometers)
- Significant Step Forward –
  Data not available till now, even in offline testing

Together with Spectrometers, this system will allow us to embark on a serious program of Continuous Online Optimization – the ultimate goal of this work

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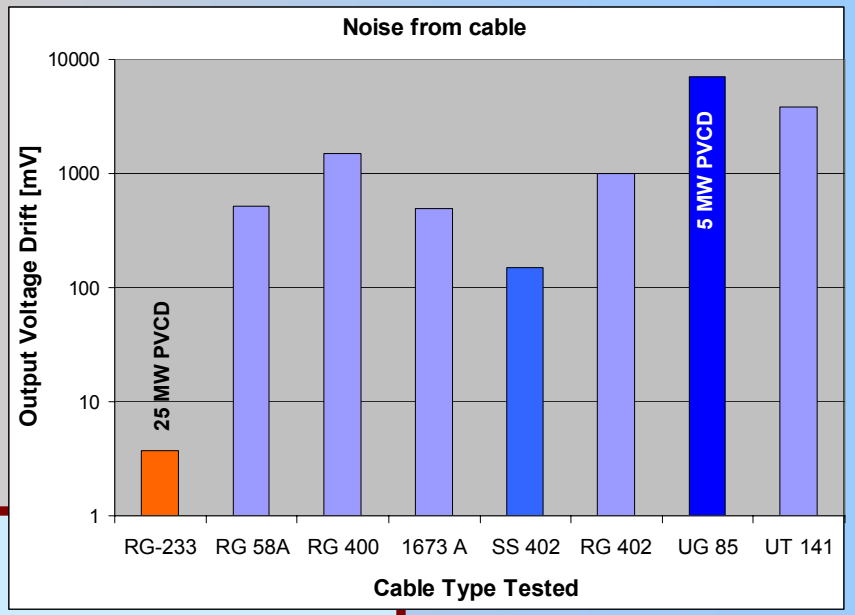
Comprehensive On-Line Closed-Loop Diagnostic Systems

Task 2: Component Cell PVCD

Design

- Challenges
- Shutter System
- Design Summary
- Light Source



Challenges

- Go from a few feet to a few inches --
  - (Discharge Heater, Pre-cooler, Pusher Plate, PVCD)
  - No access for calibration, viewing, testing, service
- Go from "dirty" to UHV-compatible
  - (Electronics, cables, …)
- Temperature Stabilization (0.1 °C)
- Sensor-to-web position stabilization (0.001" for 0.25%)
- EMI –
  - (rf, plasma, heaters, ionized gas …)
- Long cables

Accomplished with Shutter
- Measure "web offset voltage"
- Apply calibration signals

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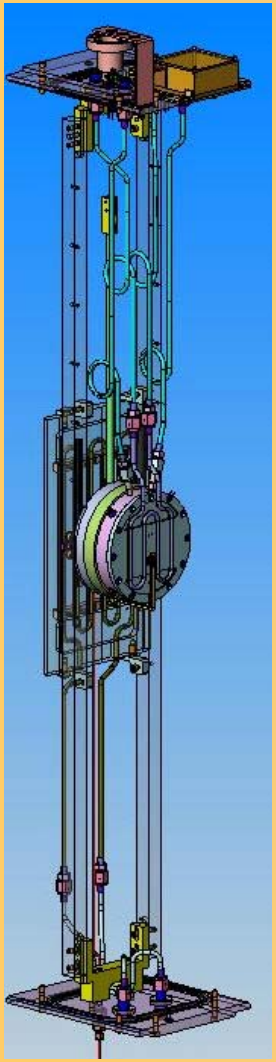
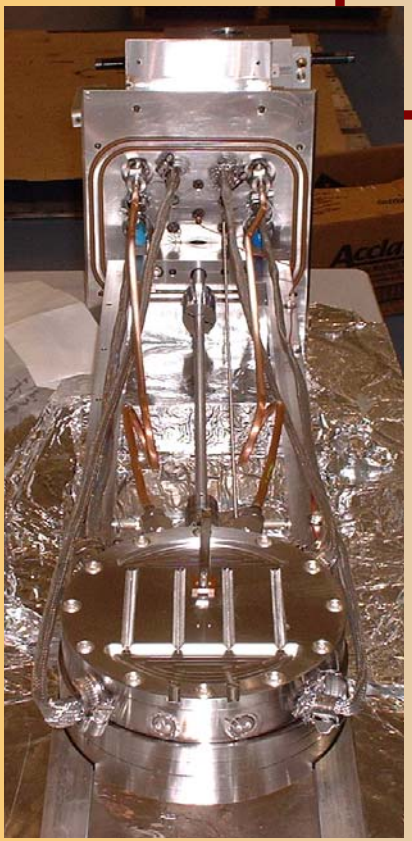
Task 2: Component Cell PVCD





Design

- Challenges
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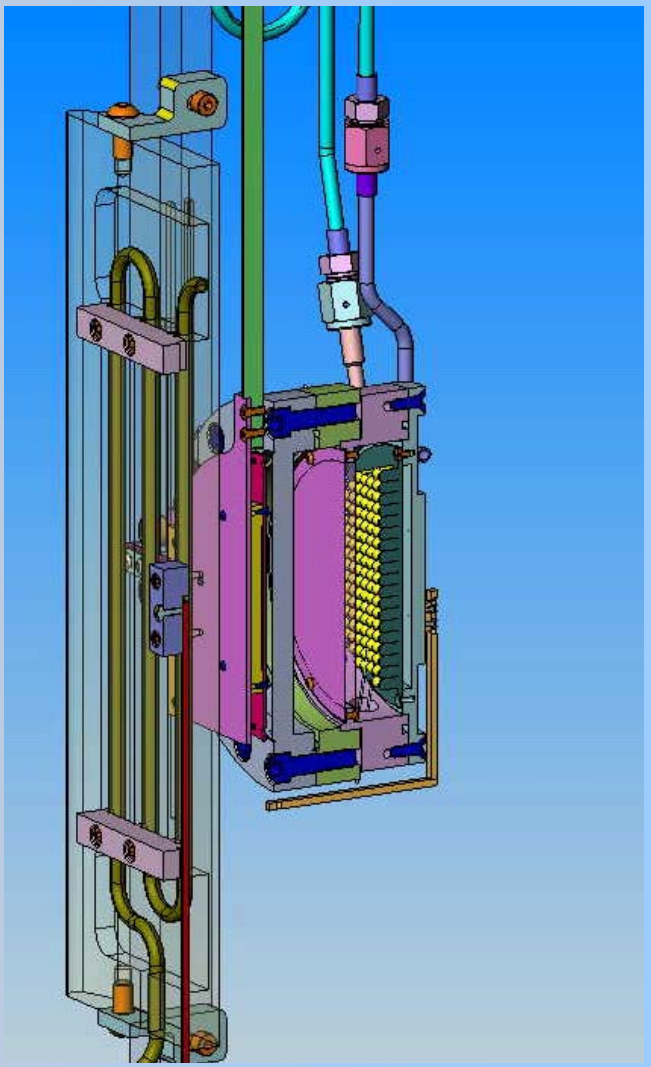
- Design Summary
- Light Source



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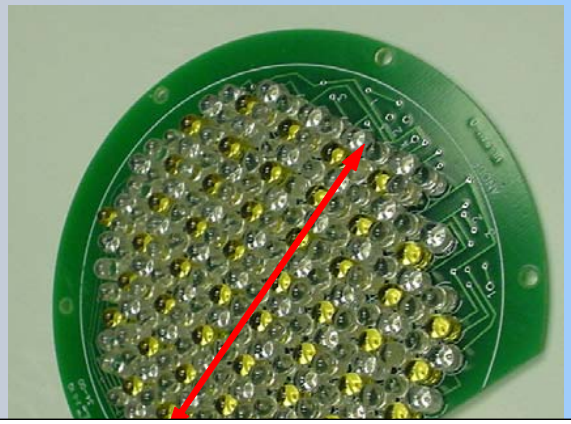
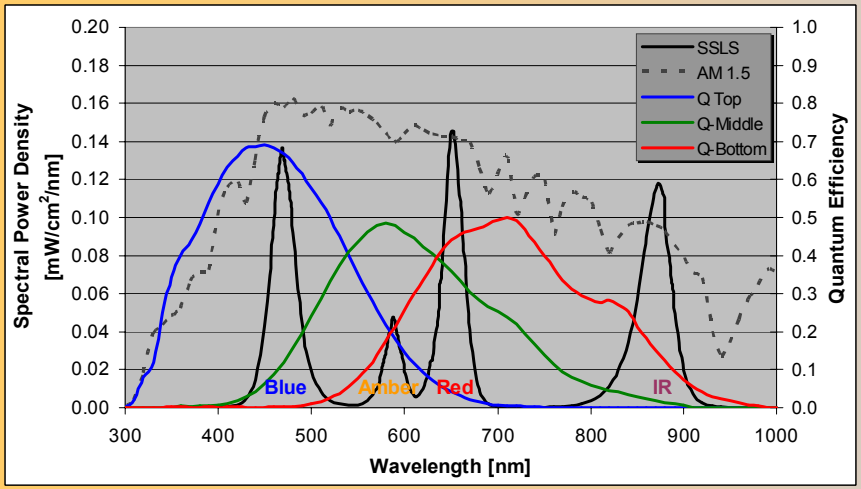
Task 2: Component Cell PVCD

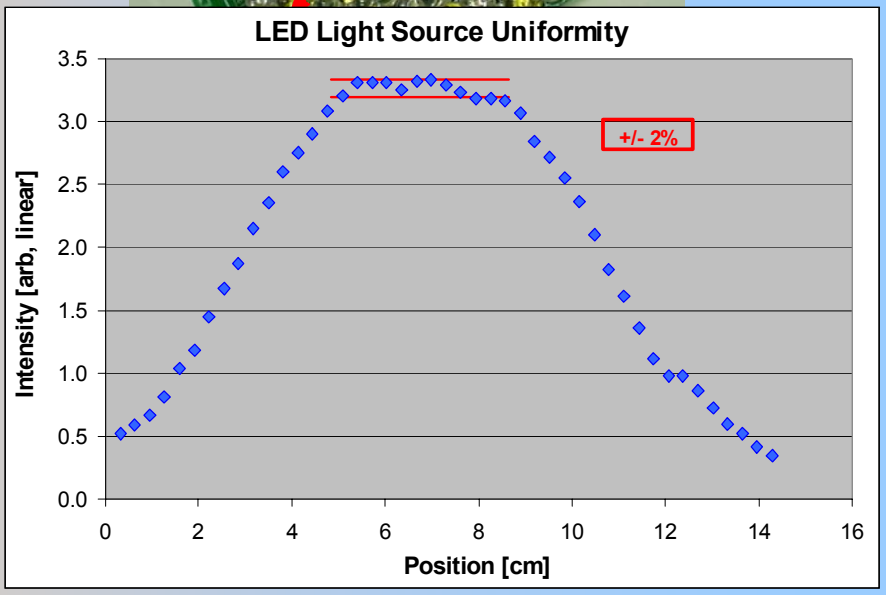
Design

- Challenges
- Shutter System
- Design Summary
- Light Source

LED	Wavelength [nm]	Absorption Top	Middle	Bottom
Blue	474	1.00	0.19	0.01
Amber	588	0.41	1.00	0.42
Red	652	0.09	0.78	1.00
IR	860	0.00	0.13	1.00







Has lead to work on an AM 1.5 Class A+ Simulator

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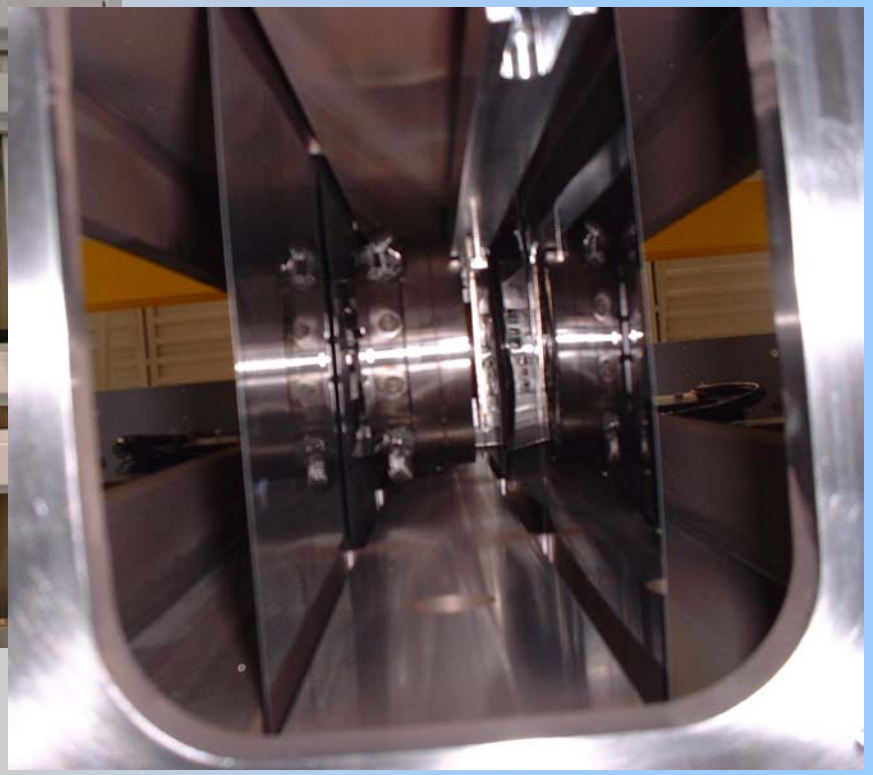
Component Cell PVCD: Installation (x3)

The Old "Ship-in-the-Bottle" Trick
Improvements:
- Notch I-Beams
- More robust feedthroughs and electrical connections
- Better "Pusher Plate" coatings



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Task 2: Component Cell PVCD

Optimization

First Operation/Noise

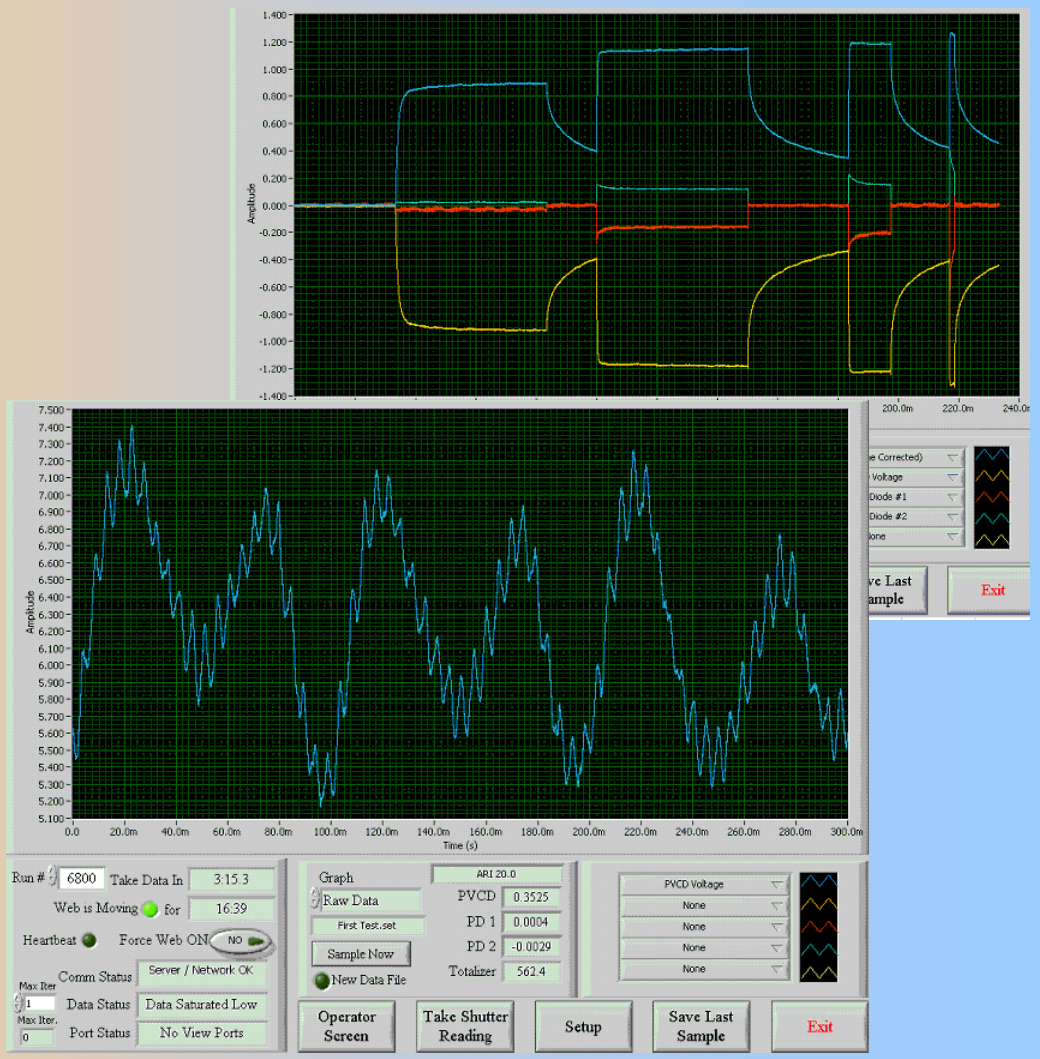
Plasma Noise Killer

Operated splendidly with plasma's and heaters off

With system operating, signal-to-noise ratio (S/N) ≈ 0.5

Was not clear that the system would work

Note – this plasma noise signal may turn out to be a useful diagnostic system –



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Optimization

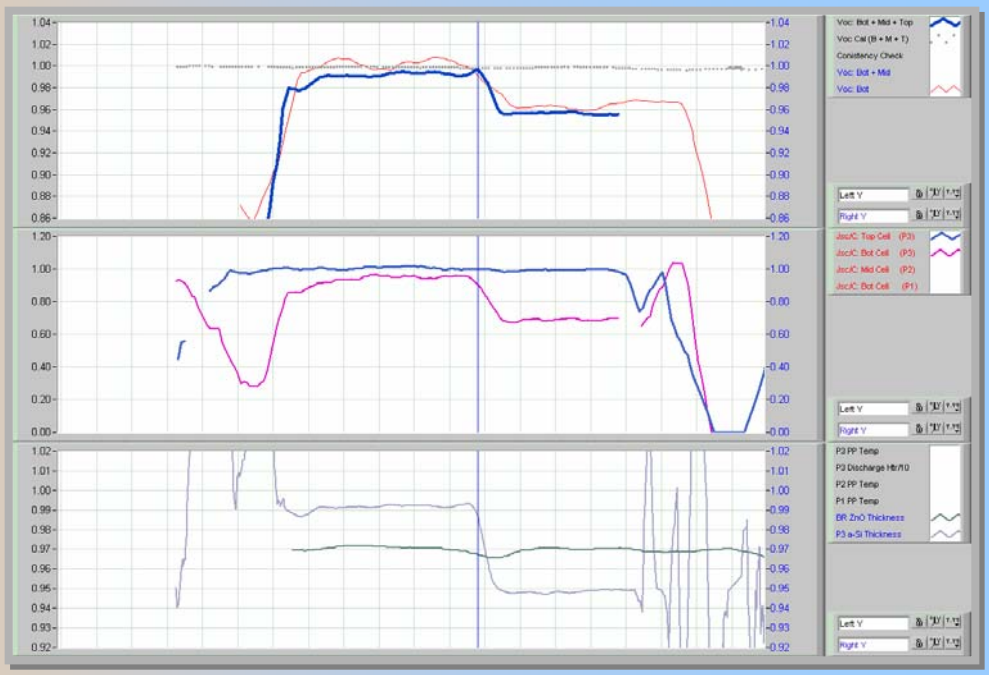
First Operation/Noise

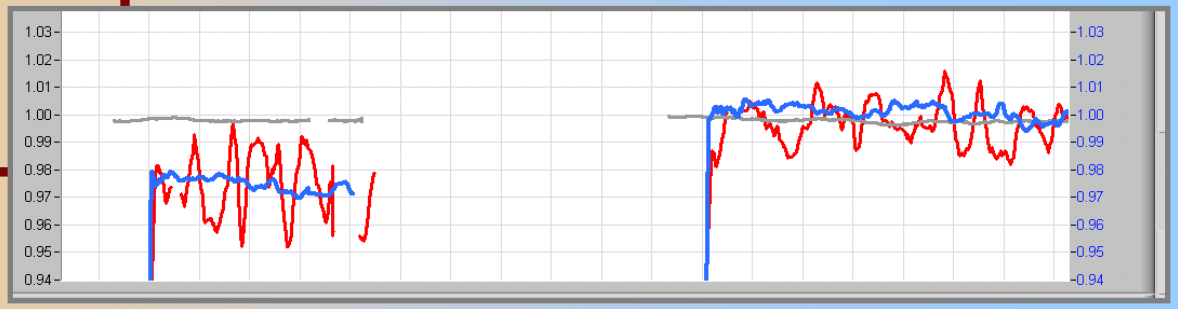
Plasma Noise Killer

Averaging
Line-sinking
"Improbability Filter"
Subtracting initial baseline
Analytical waveform fitting
Post-filtering of waveform parameters
S/N ≈ 20 (100 X)

Note: Filtering/Averaging reaches point of diminishing returns –
S/N ~ 1/√#samples

Did provide useful information
But too slow …
Too noisy for future online optimization





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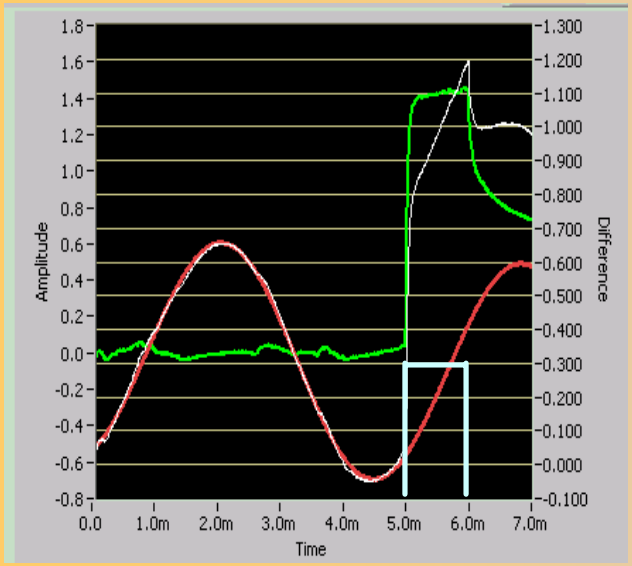
Task 2: Component Cell PVCD

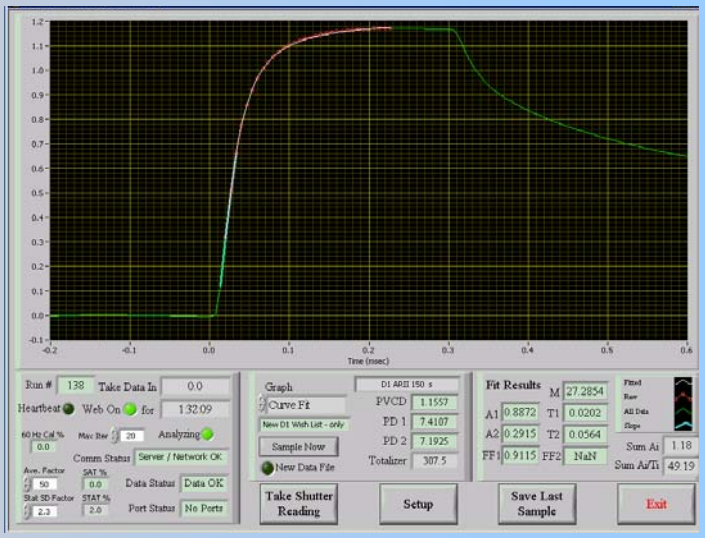
Optimization

First Operation/Noise

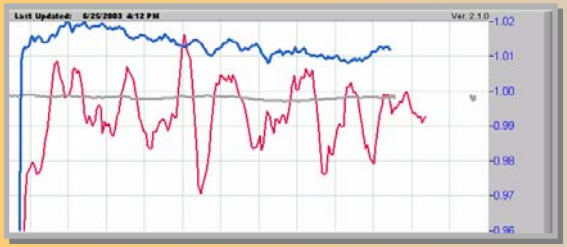
Plasma Noise Killer

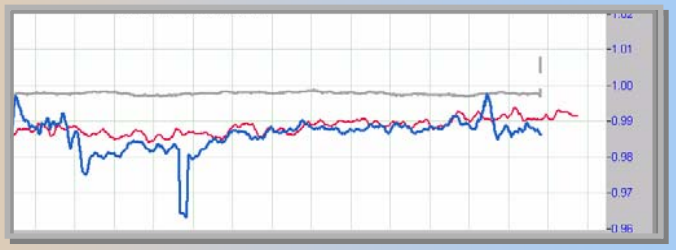
S/N now almost 1000
Perhaps better than TU Chamber System





Before





After

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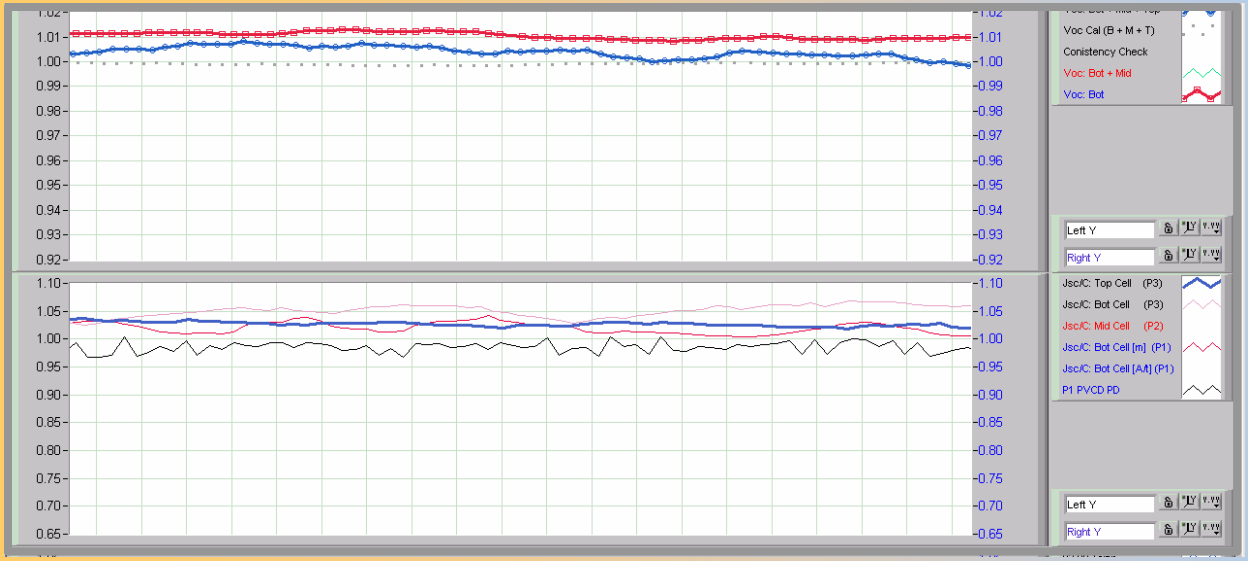
Comprehensive On-Line Closed-Loop Diagnostic Systems

Task 2: Component Cell PVCD

Summary



S/N been improved by about a factor of 10,000
Still Tweaking
All work can be applied to next generation system for the [Bottom+Middle] PVCD
Clear mechanical improvements identified
S/N and stability appear adequate for envisioned program of Continuous Online Optimization – ***the ultimate goal***

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TASK 3: Plasma Diagnostics

-- **Scott Jones**, Greg DeMaggio, and Tim Laarman (ECD)

Milestones

Complete	m-1.0.3	Initial installation of plasma monitoring sensors in pilot deposition machine.
Complete	m-1.1.3.	Complete installation of plasma monitoring sensors in pilot deposition machine.
Complete	m-1.2.2	Initial characterization of plasmas created at 1 Å/s in pilot deposition machine.
~ 1 month	m-1.4.3	Complete characterization of plasmas created at 1 Å/sec in pilot chamber.
~ 1 month	m-1.4.4	Complete the Phase I portion of the effort under Task 3.

Deliverables

~ 1 month	D-1.4.1	Summary report of characterization studies of plasmas at 1 Å/sec in pilot deposition machine

Diagnostic Systems –

Plasma Emission Spectrometer –
- Hardware
- Can we discern differences between plasma characteristics at low and high deposition rates?
  - In intrinsic-type deposition conditions?
  - In p-type deposition conditions?

Particle (powder) Detection –
- Powder is BAD –
  - Reduces deposition rates
  - Can lead to shunts in final product

Would any of these techniques be applicable to operations?

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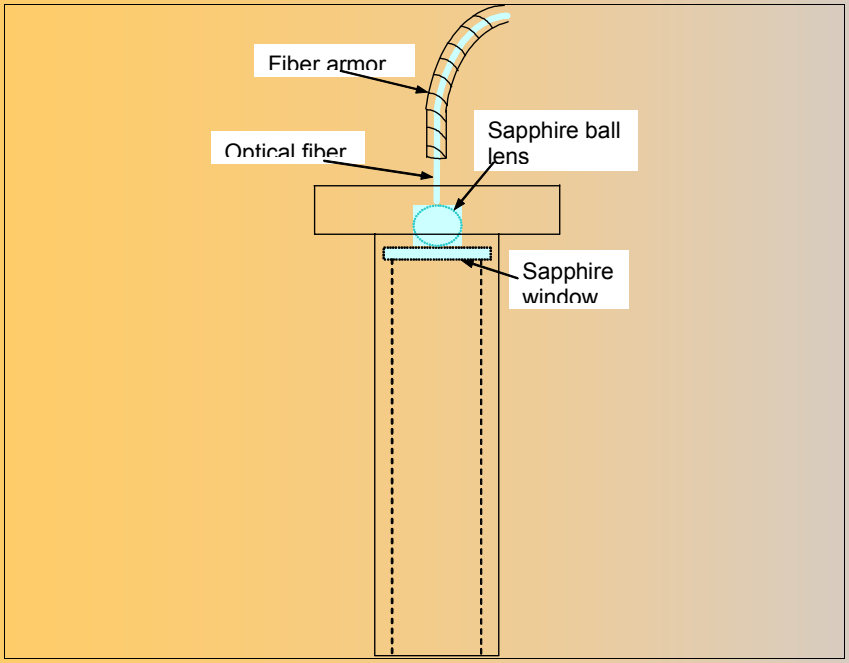
Plasma Emission Spectrometer – Hardware



Design Challenges

High Temperatures
Deposition onto Optics
UHV-Compatible

Ocean Optics 2000 USB Spectrometer

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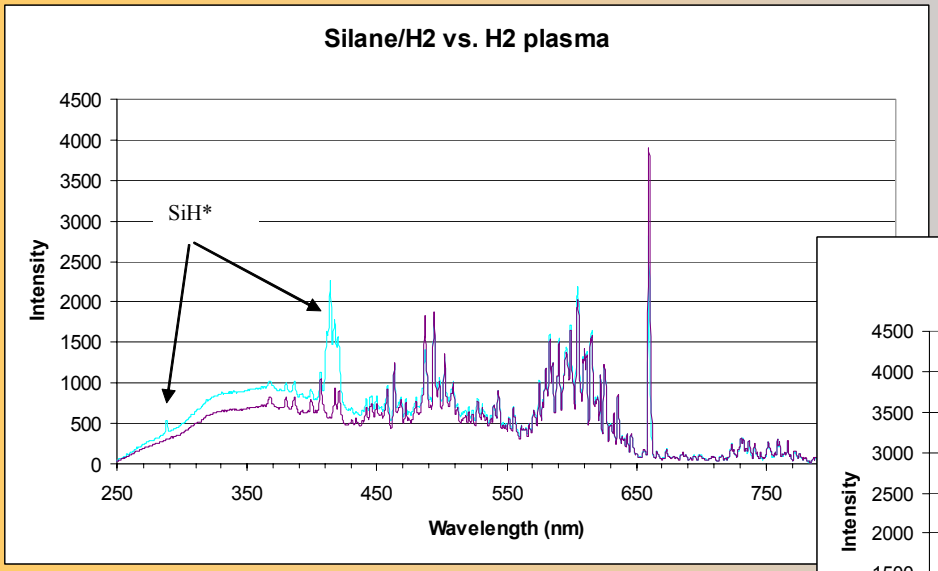
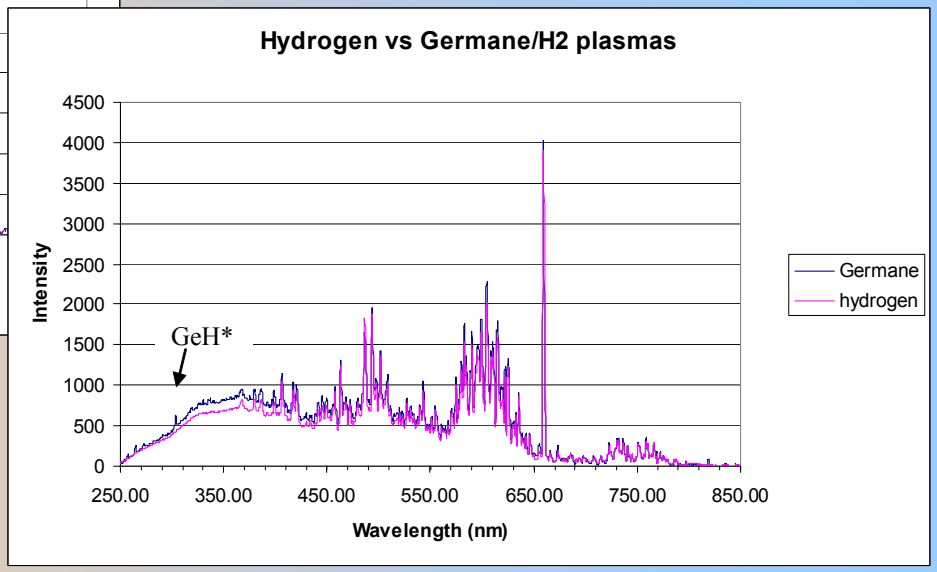
Comprehensive On-Line Closed-Loop Diagnostic Systems

Task 3: Plasma Diagnostics

Plasma Emission Spectrometer – Intrinsic-type deposition conditions

Have Looked at Si:H and Ge:H plasmas





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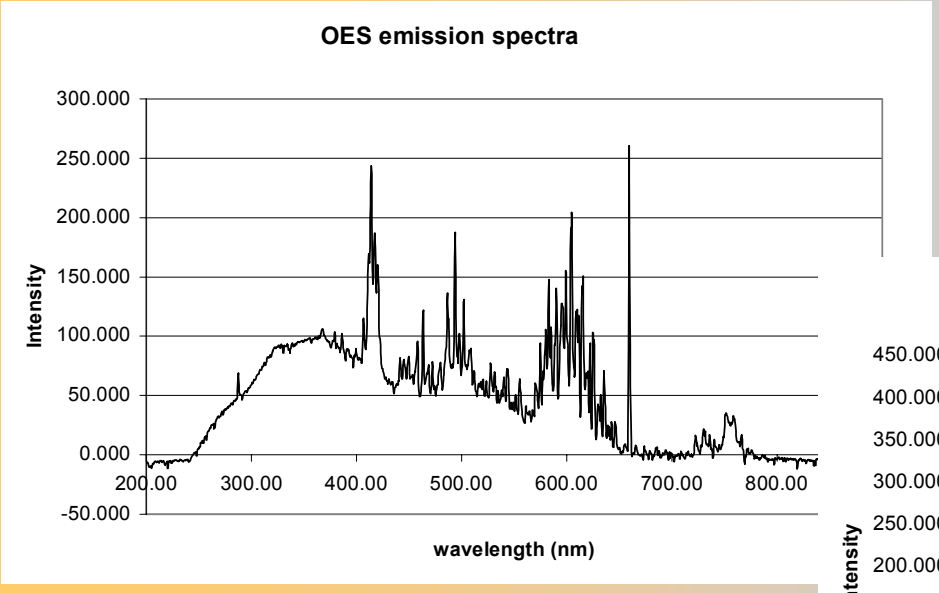
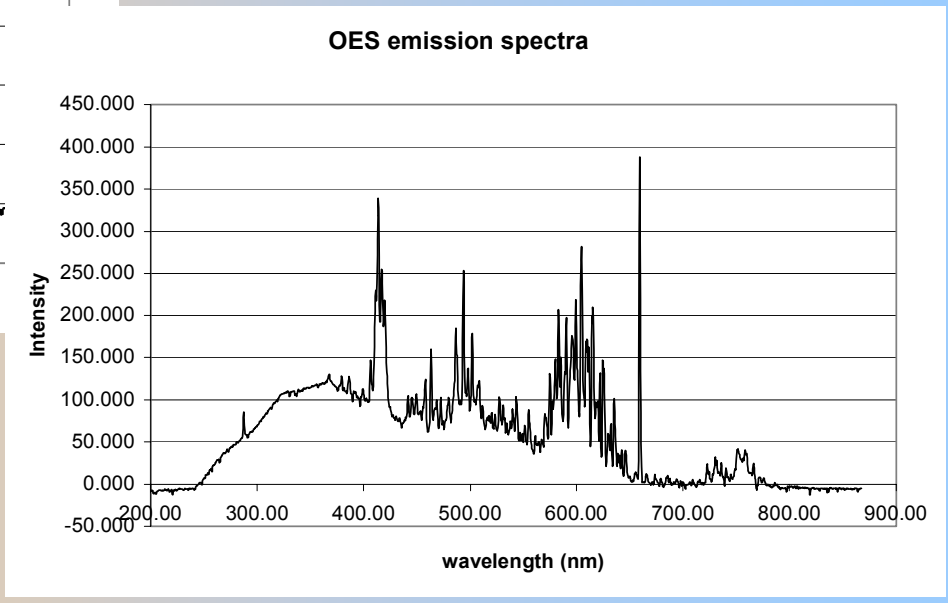
Task 3: Plasma Diagnostics

Plasma Emission Spectrometer – Intrinsic-type deposition conditions



Low (1 Å/s) and High (3 Å/s) H_2 Dilution and Deposition Rates



Operations – perhaps simple, rugged, low-cost PEM's at SiH*, GeH* and H peaks?

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Task 3: Plasma Diagnostics

Plasma Emission Spectrometer –
p-type deposition conditions

p-type deposition hardware currently being installed

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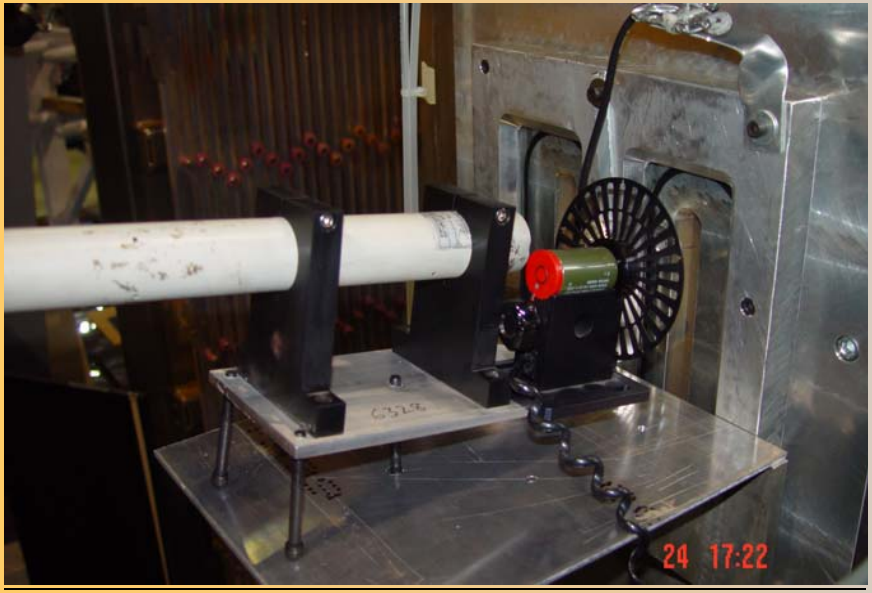
Laser Particle Detection Hardware



Have observed small response when operating with excessive powder formation conditions

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TASK 4: Yield Improvement: Substrate Cleaning and Monitoring

Greg DeMaggio (ECD), Gary Di Dio, Peter Nam, Wai Kei Chan (United Solar)

Milestones

Complete	m-1.0.4	Complete setup of OSEE Surface Quality Monitor on United Solar wash line.
Complete	m-1.1.4	Complete initial baseline characterization of surface monitor. Correlation with substrate cleaning parameters.
Complete	m-1.2.3	Complete initial investigation of plasma cleaning parameters and correlation with QA/QC data.
~ month	m-1.4.5	Complete evaluation of effectiveness of plasma cleaning vs. chemical cleaning.
In Progress	m-1.4.6	Complete evaluation of on-line techniques for measuring substrate cleanliness.
	m-1.4.7	Complete the Phase I portion of the effort under Task 4.

Deliverables

Complete	D-1.0.2	Report describing surface quality monitor on substrate wash line.
~ month	D-1.4.2	Report summarizing of plasma vs. chemical cleaning, and correlation with offline QA/QC
~ monty	D-1.4.3	Report summarizing data from cleanliness monitoring and correlation with offline QA/QC

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Comprehensive On-Line Closed-Loop Diagnostic Systems

Task 4: Yield Improvements: Substrate Cleaning

Diagnostics to Monitor Surface Cleanliness in Washing Machine

- Installation of Diagnostics
- Measurements
  - Different Substrates
  - With Varying Wash Conditions
    - Initial Testing
    - Matrix Testing

Plasma Cleaning

- Initial Measurements
- Measurements in Progress

Success in proving Plasma Cleaning works better than Wet Chemical Cleaning would allow us to eliminate one of 4 roll-to-roll Front End Processors – this is our ultimate goal.

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Diagnostics to Monitor Surface Cleanliness in Washing Machine

Installation of Diagnostics

OSEE – Optically Stimulated Electron Emission
Instrument-Substrate distance critical
A couple iterations on mounting

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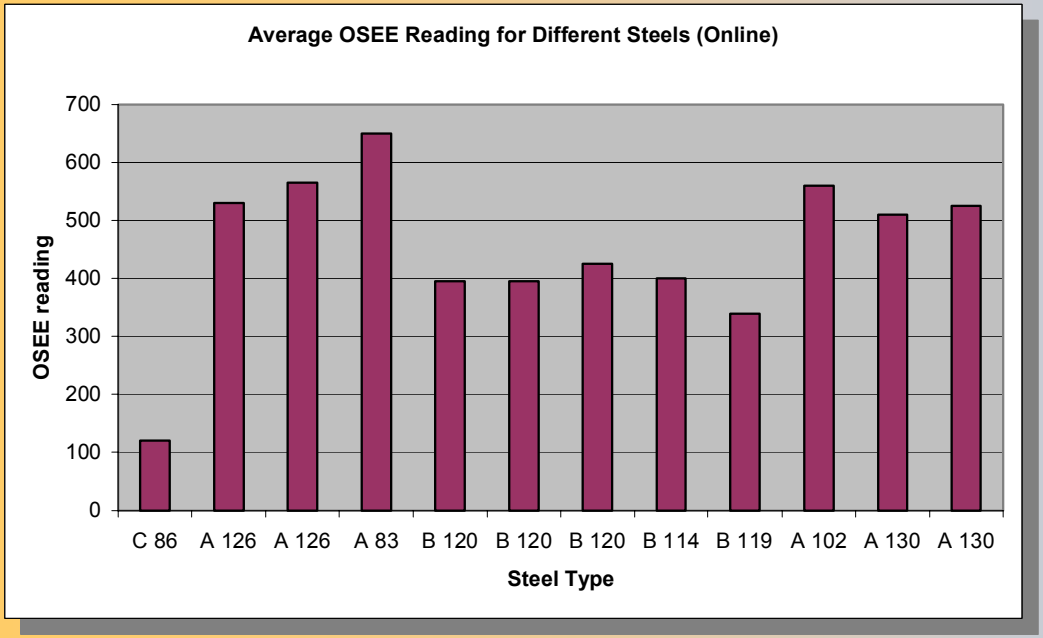
Diagnostics to Monitor Surface Cleanliness in Washing Machine

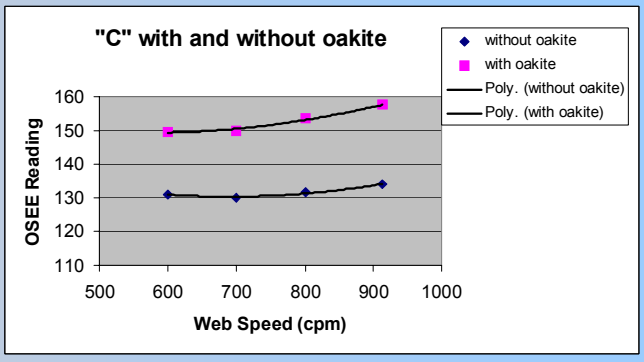
Initial Tests



OSEE signal found to vary significantly with different substrates – we found a correlation with surface finish – the higher the quality of the finish, the higher the OSEE signal.

Absolute surface contamination measurements not possible.

Also found correlations with web speed – system may still provide relative measurements to assess cleaning conditions.



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Task 4: Yield Improvements: Substrate Cleaning

Diagnostics to Monitor Surface Cleanliness in Washing Machine

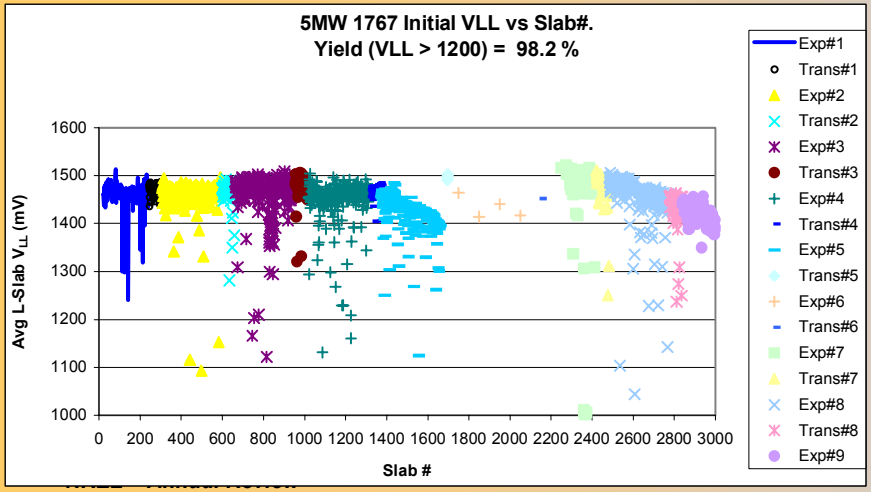
Experimental Matrix Relative Measurements

Test #	PH	Speed	OSEE reading		Difference
			PO	TU	
1	pH 8.5	600cm/min	352.7	434.8	23.3%
2		750cm/min	368.7	441.2	19.7%
3		914cm/min	370.0	433.9	17.3%
4	pH 10	600cm/min	375.5	488.3	30.0%
5		750cm/min	384.3	475.9	23.8%
6		914cm/min	391.1	475.0	21.5%
7	pH 12.3	600cm/min	397.7	665.5	67.4%
8		750cm/min	399.4	630.6	57.9%
9		914cm/min	407.1	609.2	49.6%

Results –

Increased Detergent Level (pH) increases OSEE signal –

However, no indication that OSEE signal correlates with degree of shunts in final product.



Test #	PH	Speed	OSEE reading		Difference	Average
			PO	TU	OSEE	V_{LL}
1	6.22	914cm/min	332.00	355.00	23.00	1.48
4	7.50	914cm/min	327.00	337.00	10.00	1.45
2	11.38	914cm/min	329.00	454.00	125.00	1.52
3	11.94	914cm/min	327.00	498.00	171.00	1.49

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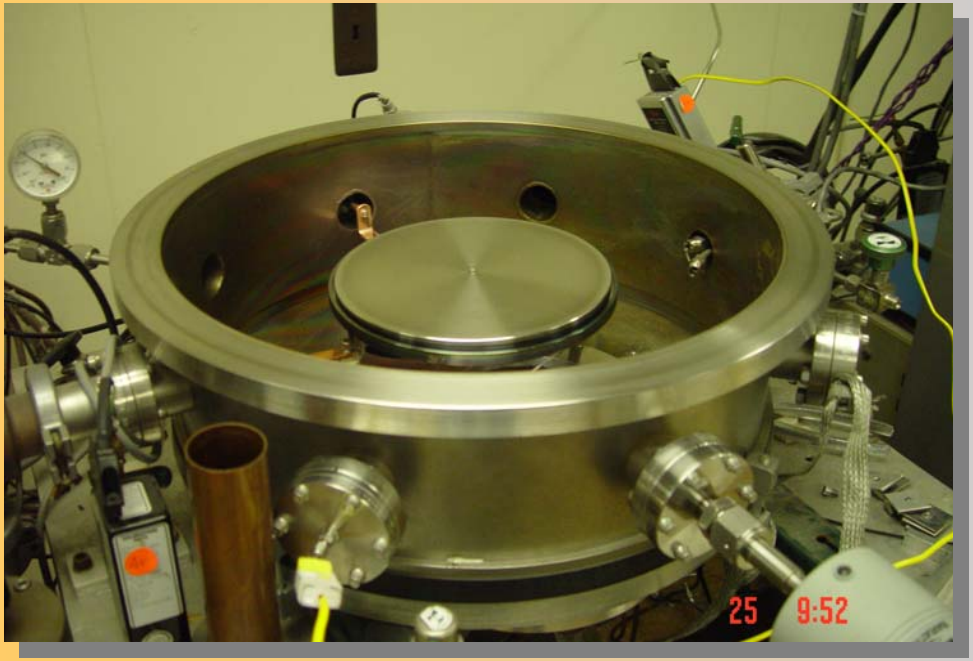
Plasma Cleaning --



Need to test offline before testing in production machines

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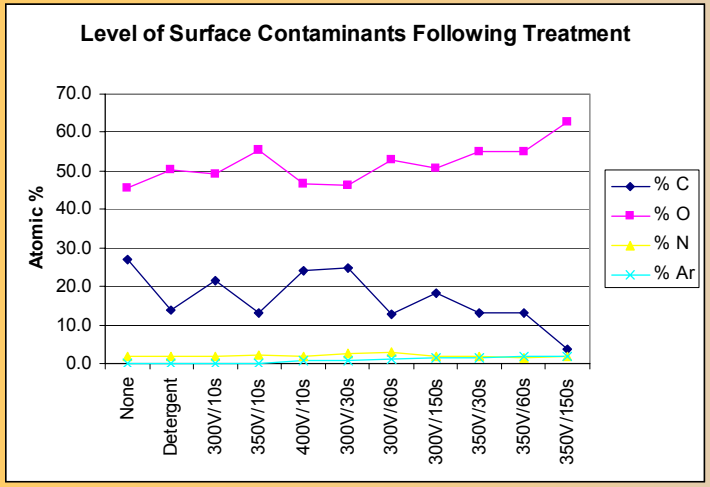
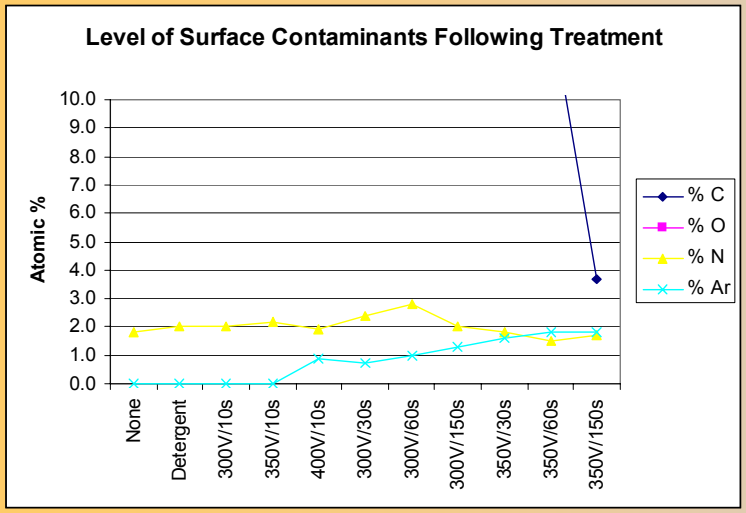
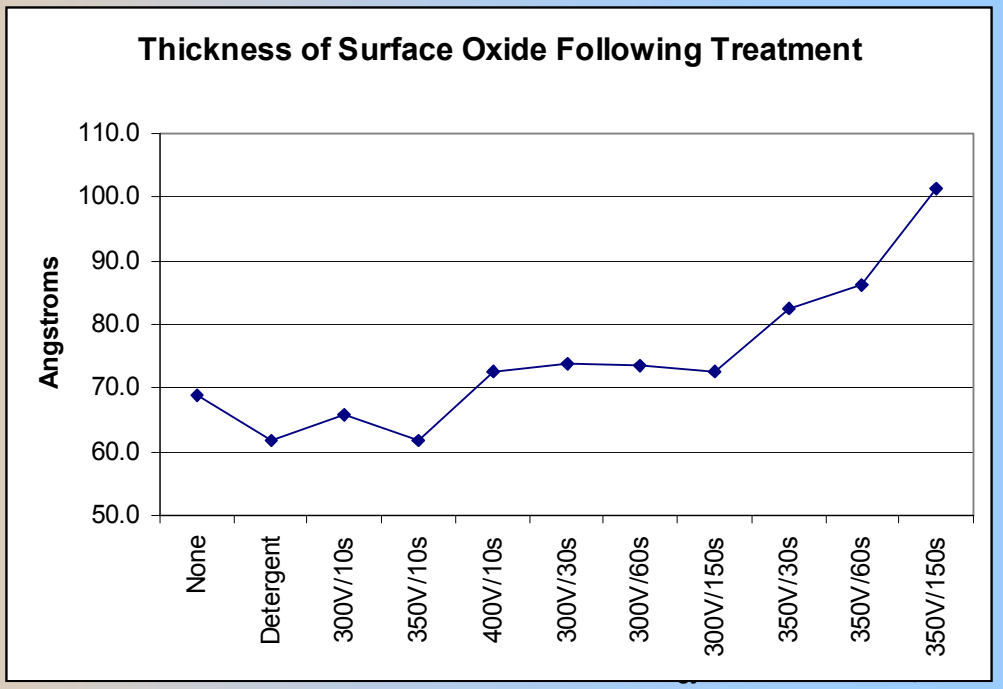
Task 4: Yield Improvements: Substrate Cleaning

Plasma Cleaning --





Comparisons between chemically-cleaned and plasma-cleaned substrates



Task 4: Yield Improvements: Substrate Cleaning

Plasma Cleaning --

In Progress –

Definitive Test –
- *Apply oil to surface of substrates*
- *Clean in Production WM and with Plasma Cleaner, varying conditions*

Does plasma cleaning provide same degree of oil cleanup as does chemical cleaning?
Can we then demonstrate cleaning this oil residue in the production BR machine

Then – trial test of substrate using plasma cleaning in BR machine w/o chemical cleaning

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Conclusions

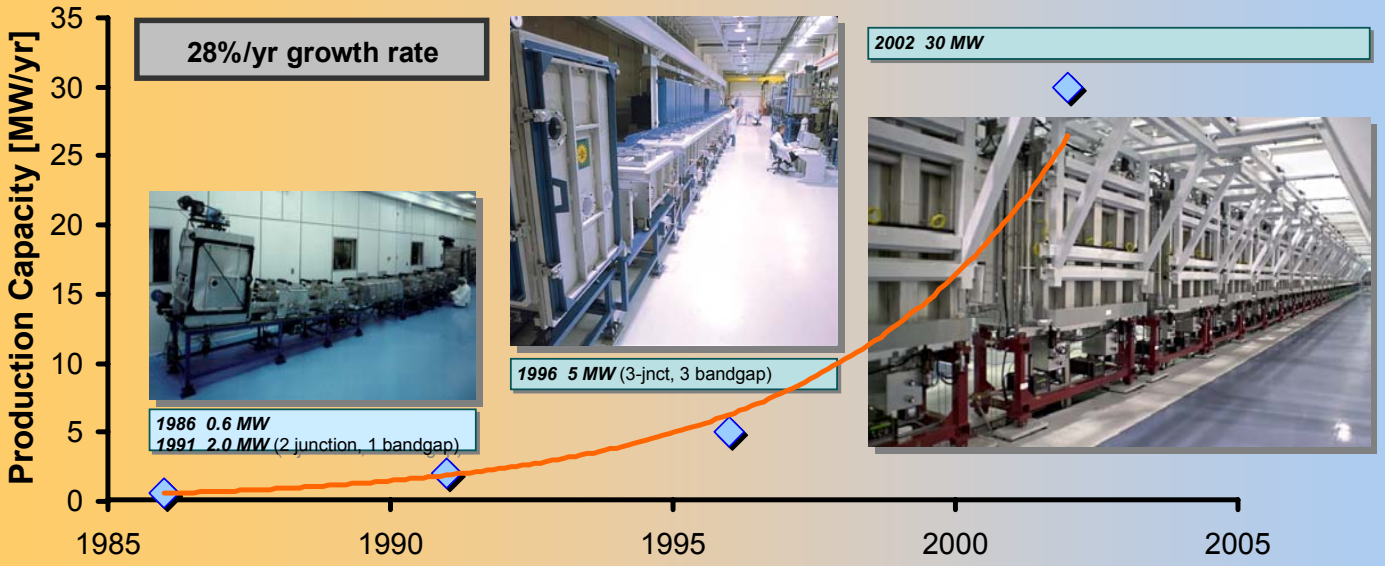
We are grateful for NREL's support.

Exponential growth

– it's an interesting thing --

To see a World in a Grain of Sand
And a Heaven in a Wild Flower
Hold Infinity in the palm of your hand
And Eternity in an hour

William Blake, Augeries of Innocence



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